PROCESS SYNTHESIS AND OPTIMISATION FOR MULTI-BIODIESEL MIXTURE PRODUCTION

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Chemical Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"PROCESS SYNTHESIS AND OPTIMISATION FOR MULTI-BIODIESEL MIXTURE PRODUCTION"** was prepared by **PANG YI WEN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Chemical Engineering at Universiti Tunku Abdul Rahman.

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ABSTRACT

Nowadays, biodiesel has been widely used as an alternative of petroleum derived diesel due to its sustainable characteristic. Biodiesel is blended with diesel and used at various concentrations. Biodiesel derived from a single kind of biological resource may not be available all year long since most biological resources are seasonal, limiting the accessibility of biodiesel. The aim of this research is to synthesise and optimise the process for multi-biodiesel mixture production used in biodiesel-diesel blending. An optimisation model is proposed to investigate the diverse biodiesel utilisation strategic in biodiesel-diesel blend production. Various factors affecting the diverse biodiesel utilisation strategic are considered such as biodiesel feedstocks, biodiesel production capacities, crude oil distillation capacities, costs and fuel properties criteria. Demonstration case study is discussed to evaluate the performance of the model. The case study is conducted based on different demand fulfilment percentage, they are 50.00 %, 65.00 %, 80.00 % and 95.00 %. As demand increases, total water transport cost increases. This is due to a more diverse biodiesel being used in biodiesel-diesel blending process. From the case study, diverse biodiesel utilisation strategic in biodiesel-diesel blend production at demand fulfilment of 65.00 % has the highest revenue amongst the cases at other demand fulfilment, which is RM 37072762.90 k/yr. The result shows that biodiesel availability, markets' demand fulfilment, location of biodiesel production plants and blending facilities have great influence in performance of diverse biodiesel utilisation strategic.

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LIST OF SYMBOLS / ABBREVIATIONS

BXX	Biodiesel Blend with XX Percentage of Biodiesel
C	Carbon
H	Hydrogen
O	Oxygen
LHV	Lower Heating Value, kJ/kg
HHV	Higher Heating Value, kJ/kg
CFPP	Cold Filter Plugging Point, ℃
MT	Metric Tonne
ML	Million Litres
k	Kilo / Thousand
i	Biodiesel production plant
h	Resource location
j	Biodiesel-diesel blending facility
k	Market
$wXX_{j,k}$	Amount of biodiesel-diesel blend with mandate BXX sent from blending facility, *j* to market, *k* in million litres per year, ML/yr
FPD	Demand of biodiesel-diesel blend fulfilment, %
dm_k	Demand of biodiesel-diesel blend in market *k*, ML/yr
$tbXX_j$	Total amount biodiesel blend BXX produced at blending facility *j*, ML/yr
tb_bXX_j	Total amount used to produce biodiesel-diesel blend BXX at blending facility *j*, ML/yr
BBXXR	Volume fraction of biodiesel blended in biodiesel-diesel blend BXX
$xXX_{i,j}$	Amount of biodiesel sent from biodiesel production plant, *i* to blending facility *j*, ML/yr
$mXX_{i,j}$	Amount of biodiesel sent from biodiesel production plant, *i* to blending facility *j*, MT/yr

db_i	Density of biodiesel produced at biodiesel production plant *i*, kg/L
$bstc_i$	Annual biodiesel production capacity at biodiesel production plant *i*, MT/yr
fr_i	Amount of feedstock required for biodiesel produced at biodiesel production plant *i*, MT/yr
cx_i	Conversion of bio-oil to biodiesel at biodiesel production plant *i*, %
$supply_{i,h}$	Supply of feedstock from resource location *h* to biodiesel production plant *i*,
$bftc_h$	Feedstock available in resource location *h*, MT/yr
yXX_j	Amount of diesel blended in BXX at blending facility *j*, ML/yr
D_C	Ratio of amount of diesel obtainable from crude oil to crude oil refined
bd_cdc_j	Crude oil distillation capacity at blending facility *j*, ML/yr
$d\_b\_bXX_j$	Density of biodiesel mixture in BXX at blending facility *j*, kg/L
d_bXX_j	Density of biodiesel-diesel blends BXX at blending facility *j*, kg/L
μ	Kinematic viscosity of biodiesel mixture or biodiesel-diesel blends obtained at 40 °C, mm^2/s
$kv\_b\_bXX_j$	Biodiesel mixtures' kinematic viscosity in BXX at blending facility *j* obtained at 40 °C, mm^2/s
kv_bXX_j	Biodiesel-diesel blend BXX's kinematic viscosity at blending facility *j* obtained at 40 °C, mm^2/s
$cn\_b\_bXX_j$	Cetane number of biodiesel mixture in BXX at blending facility *j*
cn_bXX_j	Cetane number of biodiesel-diesel blends BXX at blending facility *j*
z	Revenue, RM 10 k/yr
ts	Total sales, RM 10 k/yr
tfc	Total feedstock cost for biodiesel production, RM 10 k/yr
$tbpc$	Total biodiesel production cost, RM 10 k/yr

$tbdpc$	Total biodiesel-diesel blend production cost, RM 10 k/yr
ttc	Total truck transportation cost, RM 10 k/yr
twc	Total water transportation cost, RM 10 k/yr

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Energy is unquestionably one of the most significant driving forces for developing and advancing a nation. Besides playing an essential role in economic development; it is decisive in ensuring the prosperity and continuous growth of a nation. With the increasing global population and consequently, growing of global economic, global primary energy consumption grew rapidly in year 2018 with a rate of 2.9 %. It has the fastest growing rate since year 2010, almost twice its 10 years average with value 1.5 % per year (BP, 2019). Climate change also lead to this situation as people in some regions experiencing colder than normal winter or extraordinary hot summer, hence, stronger heating and cooling needs have to be fulfilled (International Energy Agency, 2019). Leading by natural gas which accounted for more than 40 % of the increase in energy consumption, demands for all fuels rise faster than their respective 10 years averages. As shown in Figure 1.1, non-renewable fossil fuel including crude oil, natural gas and coal supplied more than 60 % of the energy needs in 2018. Consequently, energy related carbon dioxide (CO_2) emissions grew 1.7 % to a new high of 33.1 Gt of CO_2. Use of coal alone in energy generation surpassed 10 Gt CO_2, mostly in Asia (International Energy Agency, 2019).

Figure 1.1: Breakdown of Energy Consumption by Energy (Enerdata, 2019)

For over a century, fossil fuels have and continued to be a dominant ingredient in global energy systems. As a fundamental driver of the Industrial Revolution, fossil energy also helped in the development progress of technological, economic and social of the world. Aside being a valuable source of energy, fossil fuels are also being used as feedstock in other materials production such as polyvinyl chloride (PVC). Nevertheless, use of fossil fuels has taken a massive toll on humanity and the environment. It is the major culprit for air pollution, water pollution and global warming.

Despite being one of the main contributors to the world development, emission of greenhouse gases from their use and depletion of fossil fuels have forced many researchers to work in finding alternatives to replace fossil fuels. A more environment friendly source of energy, biofuels including bioethanol and biodiesel have been developed in the way to move to a clean energy future. The charts in Figure 1.2 has showed the progress of world biofuels production. The world is paying more attention in biofuels, resulting in an average growth of 9.7 % for biofuels production in year 2018. This is the highest growth since year 2010 (BP, 2019). From Figure 1.2, the production of biodiesel showed a significant increase. North, South and Central America have almost three folds the 2008 biodiesel production in year 2018. This indicates that biodiesel has great potential in replacing petroleum-based diesel.

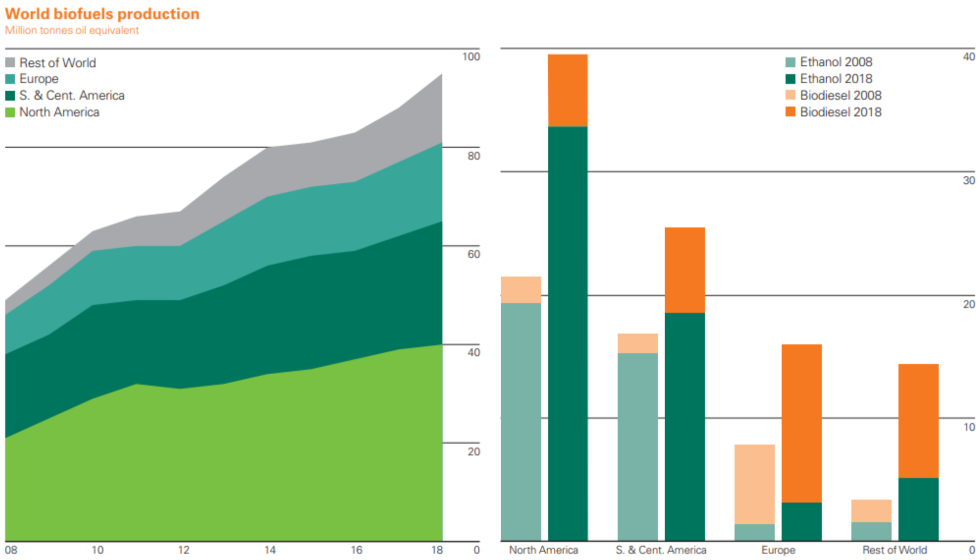

Figure 1.2: World Biofuels Production (BP, 2019)

1.1.1 Biodiesel as Alternative

Biodiesel is a clean burning fuel comprises of alkyl esters derived from either transesterification of triglycerides (TGs) or esterification of free fatty acids (FFAs) with low molecular weight alcohols (Lotero et al., 2005). The sources for FFAs or TGs used in biodiesel production are based on renewable biological resources, for example, vegetable oils, grease and animal fats. Biodiesel has been increasingly used as an alternative fuel to petroleum-based diesel since it produces less gaseous pollutants during combustion while having similar properties as petroleum-based diesel (Al-Hamamre and Yamin, 2014). Hence, biodiesel is a more environment friendly choice of fuel. In addition, biodiesel offers ease of portability and possess stability since it exists in liquid form, promoting the use of biodiesel. Besides, the by-product leftover after extraction of oil can be used as solid fuel or animal feed as it is rich in protein, generating less waste (Nag, 2008).

Potential feedstocks for biodiesel production can be categorised into edible and non-edible sources. Edible oils such as soybean, canola, and palm oils are the main sources for biodiesel manufacture with soybean oil leading in the United States (Drapcho et al., 2008). Major potential sources for biodiesel production are algal- and plant-derived because these sources consume carbon dioxide and directly utilize the sun as their source of power. Animal and fungal sources derive their energy mainly from other carbon sources, making them to provide a lesser extent to biodiesel feedstocks. The type of feedstock used greatly influencing the price of biodiesel as feedstock cost contributes around 88.00 % of the biodiesel production cost (Haas et al., 2005).

Biodiesel produced from edible oil sources is known as first-generation biodiesel. The usage of edible sources has created concern regarding food security since the oil sources have to satisfy both demands as food and biodiesel feedstock. For example, as a needed source of protein and oil required for growth, soybeans are being produced in a great amount. To be exact, the world soybean production in the 2017/2018 was estimated to have 346.02 million metric tons (Soybean Meal INFO Center, 2018). 1 metric tonne of soybean biodiesel required 5.98 metric tonnes of soybean feed as raw material. That is around 1:6 biodiesel to soybean ratio. This indicates that a large area is needed for soybean plantation in order to satisfy both needs of soybean as food and feedstock for biodiesel production. Food security will be threatened if balance between the use of edible oil as food and biodiesel feedstock failed to achieved.

The second-generation biodiesel was developed by introducing non-edible oil like rapeseed oil as feedstock. Since rapeseed has higher oil content, raw material required for biodiesel production will be lesser compared to soybean. However, both sources may lead to deforestation and loss of agricultural land for other food crops. Again, a balance needs to be achieved to ensure food security and sufficient biodiesel supply.

The third-generation feedstock, that is microalgae-based oils is being introduced as a result of technology advancement. Biodiesel produced from microalgae-based oils has been reported to be the obvious solution in the food-fuel competition as they are able to achieve higher photosynthetic yield compared to their land plant counterparts (Charyulu Tatikonda and Naveenchandran, 2019; Sharma et al., 2018). Moreover, microalgae grown faster than plants and most microalgae contain large oil content, making microalgae oil to be potential feedstock of biodiesel (Zhang et al., 2019). However, third-generation feedstock is yet to be widely used as there are some challenges need to be overcome such as low lipid yield under limiting growth conditions (Sharma et al., 2018).

Biodiesel can be blended with diesel and used in various concentrations. B5 (up to 5 % biodiesel) and B20 (6 % - 20 % biodiesel) are the most commonly used. Pure biodiesel, also known as B100 is rarely used in transportation sector. It is the blendstock typically used for lower blends production (Alleman et al., 2016).

1.1.2 Biodiesel in Malaysia

The main biodiesel being produced by Malaysia Biodiesel Association is palm-based, that is from oil palm which is renewable and available readily in Malaysia. Based on Malaysian palm oil's multi-year full life cycle assessment conducted by Malaysian Palm Oil Board (MPOB), Malaysian palm-based biodiesel achieved attained the total greenhouse gases savings with 76 % of biogas capture. This exceeds the requirements stated in the European Commission Renewable Energy Directive year 2018, that is a minimum of 60 %. Starting June 2011, the Malaysian Government has used palm-based biodiesel in their mandatory biodiesel blending programme for uses in transport segment. B5 biodiesel was successfully announced in Malaysia in June 2011, followed by B7 in December 2014. B10 biodiesel was then introduced in year 2015. However, the implementation of B10 has been delayed because of the unfavourable crude palm oil's price compared to the price of regular diesel. In addition, most of the diesel engines in automotive being used in Malaysia were not designed to deal with B10 biodiesel. Fuel filter plugging, engine material deterioration, deposits on fuel injectors, engine oil degradation and dilution along with component damage are some of the reasons delaying the use of B10 in Malaysian transport sector (Lee, 2017). Several steps have been taken to deal with this problem.

Nevertheless, based on a verdict announced by the European Commission on March 13, 2019, biodiesel from palm oil was announced to be banned from subsidies under the bloc's Renewable Energy Directives by year 2030. This is due to the excessive deforestation resulted in cultivation of palm oil, making palm-based biodiesel not eligible to be accounted as European Union (EU) renewable transport targets. Approximately 45 % expansion of palm oil production has been claimed to cause direct deforestation since 2008, which is opposing to EU's hope of halting deforestation by 2020 (Keating, 2019). A new set of regulations with the new criteria for the use of palm oil in biofuels was then published.

Despite of the ban of palm-based biodiesel, Malaysian government continues their plan to implement biodiesel B20 in transport sector by 2020 and biodiesel B7 in industrial sector. This is due to the high oil yield achievable from oil palm. For 45 M ha of land area used for oil yield of oil palm, 5950 L ha^{-1} yr^{-1} oil can be yield from oil palm. This is considered high compared to other oil producing crops like corn that 1540 M ha of land to yield 172 L ha^{-1} yr^{-1} of oil (Kumar and Sharma, 2014). Besides, there are many farmers still working with oil palm plantation. With the use of oil palm as feedstock in biodiesel production, the farmers can gain greater profit while improving the economy of Malaysia. According to International Trade and Industry Minister, Darell Leiking, palm oil biodiesel still plays an important role to meet the needs of transportation and energy sectors in Malaysia (BLOOMBERG, 2019).

1.2 Problem Statement

Ever since the discovery of biodiesel, many researches have been conducted to yield biodiesel in a more economically favourable way. As mentioned, biodiesel cost greatly depends on the raw material price. Other costs for biodiesel production are also higher compared to the petroleum-based diesel production. Hence, optimisation of feedstock selection and supply chain are expected to help in reducing the production cost of biodiesel, maximising revenue.

Biodiesel used in transportation sector are normally blended with diesel at various concentrations. Most of the biodiesel blends available globally are produced using a single type of biodiesel with diesel. Nevertheless, biodiesel derived from a single kind of biological resource may not be available all year long since most biological resources are seasonal. In addition, harvest of biological resources, especially oil producing crops may be influenced by climate, weather and occurrence of natural disaster. Biomass supply chain may be interrupted, threatening the sustainability of blending single biodiesel with diesel. Production of biodiesel from single type of edible biological resource may cause shortage of food. Therefore, in order to ensure food security and sustainable biodiesel production, a multi-biodiesel in blending is considered.

Although production of multiple biodiesels may consume higher cost or even larger land area for oil yield, potential biodiesel feedstock being underutilised such as used cooking oil can be discovered as human are always finding ways to reduce the production cost. With this, the waste being discharged can be fully utilised, improving overall supply chain of biodiesel feedstock as alternative resources. This helps to reduce raw material cost as well as logistic cost while preventing potential environmental issues caused by direct discharge of these waste.

1.3 Aim and Objectives

The general aim of this research is to synthesise and optimise the process for multi-biodiesel mixture production with the following objectives to be achieved:

i. To analyse the relationship between multi-biodiesel mixture ratio and biodiesel performance.
ii. To determine feedstock selection criteria for diverse biodiesel system.
iii. To integrate proposed biodiesel selection model into multi-biodiesel supply chain optimisation model.
iv. To demonstrate case study of the proposed optimisation model.

1.4 Scope and Limitation of the Study

The scopes for this project are shown in Figure 1.3. There are several limitations in this study. Firstly, the optimisation model developed in this study will be based on literature reviews and data collection from other papers without conducting experiment. This may lead to inaccuracy in results obtained using this model. Next, this optimisation model is developed using GAMS only. This model is subjected to constraints of GAMS software.

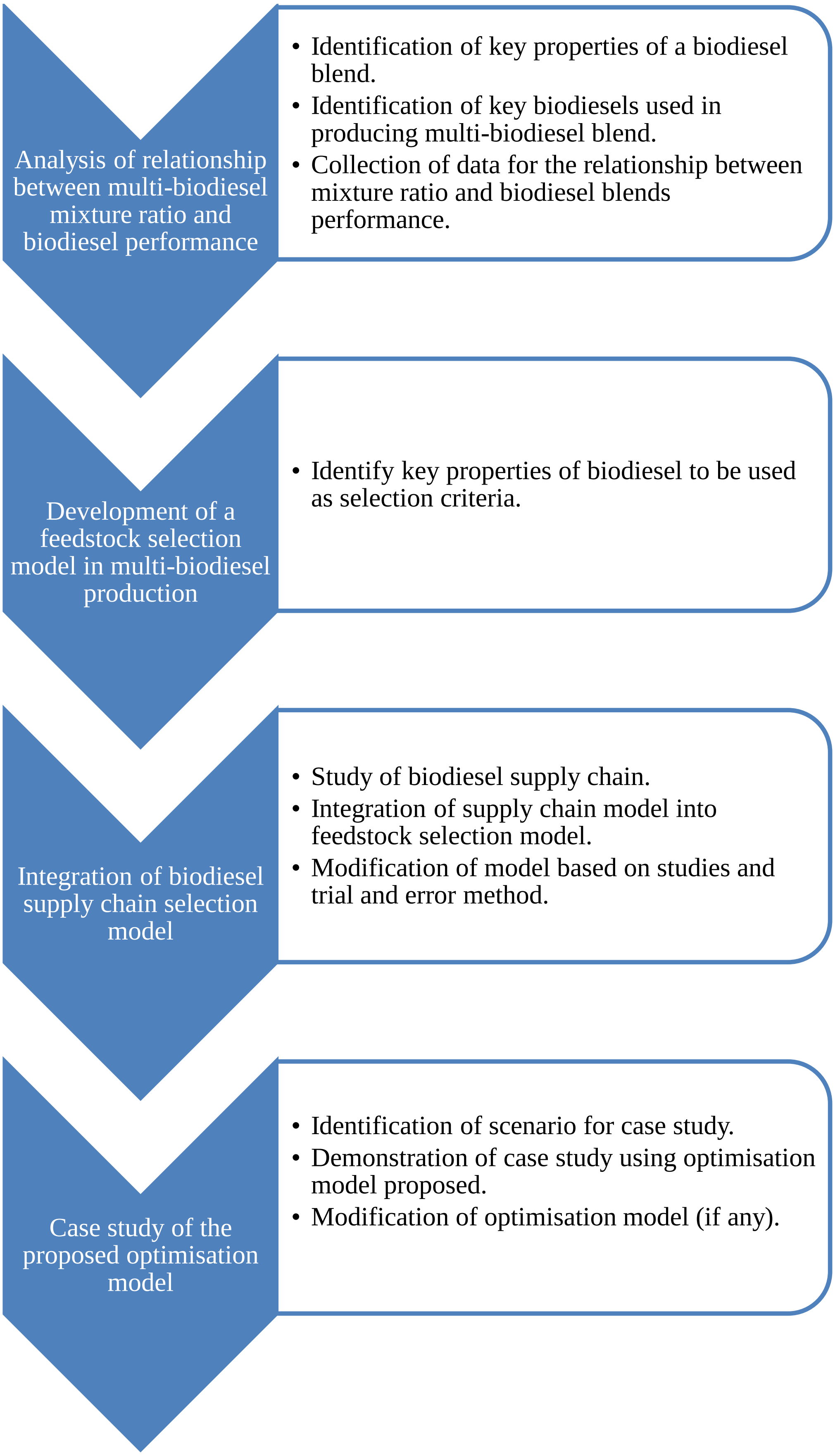

Figure 1.3: Scopes of the Project.

1.5 Contribution of the Study

Majority of this study related journals discussed in this project has not propose optimisation model to help in optimising the multi-biodiesel mixture production. With the development of a model that considering all the biomass within a supply chain will help to better understand the effect of biomass properties on multi-biodiesel blend. This proposed optimisation model also aims to provide better prediction of multi-biodiesel blend's properties using mathematical formulation.

1.6 Outline of the Report

Chapter 1 provides a brief introduction of biodiesel as well as the impacts of it towards ever increasing energy demand due to economic and national development. Problem statement along with the project's aims and objectives, scope and limitations as well as contribution of this study are also discussed in Chapter 1. Chapter 2 manifests the detailed review of various project related information and standards from different references. This included diesel properties, biodiesel blending and optimisation model that will be considered before carrying out the research. Chapter 3 defines the research methodology and planning of optimising multi-biodiesel mixture production using GAMS. Model and results obtained will be interpret and discussed in Chapter 4. Chapter 5 concludes findings from the study and gives some recommendations that can be done.

CHAPTER 2

LITERATURE REVIEW

2.1 Diesel Fuel

Diesel fuel is a heavier fraction of limited non-renewable crude oil than kerosene, comprises of a group of hydrocarbons containing 8 to 25 carbon atoms per molecules (Soares, 2015). Three quarters of this group of hydrocarbons is composed of saturated hydrocarbons while the rest is made up of aromatics (Brownstein, 2015). Diesel fuel can be obtained from fractional distillation of crude oil as medium distillate that condensed at temperature ranging from 250 ℃ to 350 ℃ (Ashraf and Aftab, 2012). Diesel fuel can also be produced by various cracking process of longer crude oil hydrocarbon chains. Due to its broader range of hydrocarbon contents, diesel fuel it is less refined, hence, having lower cost of production (Soares, 2015).

Being used as a fuel for internal combustion engines, diesel has a variety of end uses. Diesel is especially important in transportation as most of the products are delivered from manufacturers to consumers by vehicles like trucks or trains powered with diesel engines. Most farming, military, construction equipment and vehicles are also driven by diesel engines. Electricity can also be generated in a diesel engine generator using diesel as fuel. Diesel generators has been used as backup or emergency power supply in many hospitals, large buildings and industrial facilities (U.S Energy Information Administration, 2019). There are many other end uses of diesel fuel both on-road and off-road. Depends on the use of diesel, various groupings of characteristics exist and there are various classifications being used in different countries to illustrate diesel fuels (Speight, 2011b). For example, grades No.1-D and 2-D diesel defined in ASTM D-975 in the United States are more commonly used in portable type high-speed engines, in railroad engines and in stationary engines with medium speed. Table 2.1 shows Malaysian diesel fuel general requirement as stated in MS 123-1:2014.

Table 2.1: Test Method and Limits for Diesel Fuel as Specified in MS 123-1:2014 (Liang Yung and Kheang Loh, 2018)

Property	Test Method	Limits		Units
		Min	Max	
Colour (ASTM)	ASTM D1500	-	2.5	-
Kinematic Viscosity, at 40 °C	ASTM D445	1.5	5.8	mm^2/sec.
Density at 15 °C	ASTM D4052	0.81	0.87	kg/L
Flash Point	ASTM D93	60	-	°C
Cloud Point	ASTM D2500	-	19.0	°C
Cetane Number	ASTM D6890	49	-	-
Acid Number	ASTM D664	-	0.25	mg KOH/g
Ash	ASTM D482	-	0.01	mass %
Total Sulfur	ASTM D5453	-	500	mg/kg
Water Content	ISO 12937	-	-	mg/kg
Water by Distillation	ASTM D95	-	0.05	vol.%
Sediment by Extraction	ASTM D473	-	0.01	mass %
Copper Corrosion (3 h at 100 °C)	ASTM D130	-	1	Rating
Carbon Residue on 10 % Bottoms	ASTM D189	-	0.2	mass %
Physical Distillation at 95 % Recovered Volume	ASTM D86	-	370	°C
Lubricity	ASTM D6079	-	460	µm
Electrical Conductivity	ASTM D2624	50	-	pS/m

2.2 Biodiesel as an Alternative

In consideration of climate change, fast exhausting fossil fuel resources and increasing energy demand and petroleum price, man urge in finding alternative fuels. Production technology, process improving catalyst and the types of feedstock being used are currently studied worldwide after the introduction of biodiesel as an alternative fuel.

Biodiesel is mainly comprising of alkyl esters generated from biological source such as vegetable oils, grease, algae and animal fats. Transesterification of TGs or esterification of FFAs with low molecular alcohols, for instance methanol and ethanol can produce alky esters which is the main component in biodiesel (Sandouqa, Al-Hamamre and Asfar, 2019). As most of the diesel engines available currently are intended to be power-driven by diesel fuel, biodiesel being introduced as alternative should have similar properties with diesel so that biodiesel can be used solely or as a diesel blend mixture for diesel engines without engine design modification. Various factors need to be considered when characterising the quality of a biodiesel. Some of the factors are the quality of feedstock, process technology and parent feedstock's fatty acid content. These factors will influence the physical and chemical properties of a biodiesel, hence, affecting the performance of a diesel engine (Barabas and Todoru, 2011).

Unlike conventional diesel fuel obtained from crude oil which is a mixture of paraffinic, aromatic and naphthenic hydrocarbons, biodiesel contains unsaturated and saturated long chain fatty acids derived mono-alkyl esters. The differences in their chemical nature resulted the differences in their basic properties (Qi and Lee, 2014). General properties of conventional diesel and biodiesel fuels are showed in Table 2-2. From Table 2.2, biodiesel has a narrower range of carbon content per molecule. With the presence of oxygen in biodiesel, molecular weight and specific gravity of biodiesel is greater. Lesser harmful pollutants and emissions can be achieved with more complete combustion because of the fact that biodiesel is oxygenated (Candeia et al., 2009).

Furthermore, biodiesel with alkyl ester which is having higher polarity than normal paraffins causes biodiesel has higher boiling point, autoignition point and flash point compared to conventional diesel fuel. Safer handling and storage of biodiesel can be achieved. However, higher boiling point of biodiesel means lower volatility. This will result in poor starting and warm-up performance if no proper care is taken. Heating value is the amount of heat energy being released during combustion. Heat of combustion decreases with chain length. This may be the reason of biodiesel's lower heating values compared to diesel (Knothe et al., 2010). Biodiesel is a suitable alternative for conventional diesel as both are having similar properties.

Table 2.2: General Properties of Petrol-Diesel and Biodiesel (Speight, 2011a)

		Diesel Fuel (Petro-diesel)	**Biodiesel**
Chemical Formula		C8 – C25	C12 - C22
Composition (wt%)	**C**	87	77
	H	13	12
	O	-	11
Molecular Weight		200	292
Specific Gravity		0.850	0.880
Boiling Point (°C)		180 - 340	315 - 350
Autoignition Temperature (°C)		315	-
Flash Point (°C)		60 - 80	100 - 170
Heating Values (kJ/kg)	**LHV**	42,800	37,500
	HHV	45,800	40,200
Flammability Limits (vol%)		1.0 - 6.0	-

2.2.1 Quality Standards of Biodiesel

There is no one standard that can characterise the quality of all biodiesel due to the variety factors which changes from area to area. For example, the present diesel fuel standards, the most common types of diesel engine being used in that area, engines' emission regulations, climatic properties of the area where the biodiesel is produced and used, and the purpose of that biodiesel use. Standards used to characterise quality of biodiesel are continuously updated primarily resulted from ever stricter emission regulations, evolution of compression combustion engines and re-evaluation of the suitability of biodiesel production feedstocks (Barabas and Todoru, 2011). There are various quality standards of biodiesel available worldwide. Selection of the standard used will depends greatly on the type of biodiesel being produced or used and the area where these activities are carried out.

Malaysian Palm Oil Board (MPOB) has developed Malaysian Standard of Palm Methyl Ester (MS 2008) based on European standard EN 14214 with the adoption of both EN/ISO and ASTM testing methods. MS 2008 has been revised and published in year 2014. The revised version of MS 2008 is showed in Table 2.3 while Table 2.4 and Table 2.5 tabulated the quality standard used for biodiesel in European countries and the United States respectively. Both Malaysian and European biodiesel standards are only applicable for fatty acid methyl esters (FAME) whereas the American biodiesel standard is applicable for both FAME and fatty acid ethyl esters (FAEE). Besides, the American standard define a product that will be used as a blending component for conventional diesel fuel while the product under both Malaysian and European biodiesel standards can be used either as a blending component with petroleum diesel fuel or a stand-alone fuel for diesel engines (Barabas and Todoru, 2011).

Table 2.3: Biodiesel Standard MS 2008: 2014 (Malaysia)

Property	Test Method	Limits		Unit
		Min	Max	
Viscosity at 40 °C	ISO 3104, ASTM D 445	3.5	5.0	mm^2/s
Density at 15 °C	ISO 3675, ISO 12185 ASTM D 4052, ASTM D 1298	860	900	kg/m^3
Flash Point	ISO 2719, ISO 3679, ASTM D 93	120	-	°C
CFPP	EN 116		15	°C
Cetane Number	ISO 5165, ASTM D 613, ASTM D 6890	51.0	-	-
Oxidative Stability, 110 °C	EN 14112, EN 15751	10.0	-	hours
Acid Value	EN 14104, ASTM D 664	-	0.50	mg KOH/kg
Linolenic Acid Content	EN 14103	-	12.0	% (m/m)
FAME Content	EN 14103	96.5	-	% (m/m)

Table 2.3 (Continued)

Property	Test Method	Limits		Unit
		Min	Max	
Polyunsaturated (≥ 4 double bonds) Methyl Esters	EN 15779	-	1	% (m/m)
Monoglyceride Content	EN 14105, ASTM D 6584	-	0.70	% (m/m)
Diglyceride Content	EN 14105, ASTM D 6584	-	0.20	% (m/m)
Triglyceride Content	EN 14105, ASTM D 6584	-	0.20	% (m/m)
Methanol Content	EN 14110	-	0.20	% (m/m)
Free Glycerol	EN 14105, EN 14106, ASTM D 6584	-	0.02	% (m/m)
Total Glycerol	EN 14105, ASTM D 6584	-	0.25	% (m/m)
Sulfur Content	ISO 20846, ISO 20884, ISO 13032, ASTM D 5453	-	10.0	mg/kg
Sulfated Ash Content	ISO 3987, ASTM D 874	-	0.02	% (m/m)
Water Content	ISO 12937, ASTM E 203, ASTM D 6304	-	500	mg/kg
Total Contamination	EN 12662	-	24	mg/kg
Copper Strip Corrosion (3 hours, 50 °C)	ISO 2160, ASTM D 130	Class 1		rating
Iodine Value	EN 14111, EN 16300	-	110	g I /100 g
Group 1 Metals (Na + K)	EN 14108, EN 14109, EN 14538	-	5.0	mg/kg
Group II Metals (Ca + Mg)	EN 14538	-	5.0	mg/kg
Phosphorus Content	EN 14107, ASTM D 4951	-	4.0	mg/kg

Table 2.4: Biodiesel Standard EN 14214 (European) (Zahan and Kano, 2018)

Property	Test Method	Limits		Unit
		Min	Max	
Viscosity at 40 °C	EN ISO 3104, ISO 3105	3.5	5.0	mm^2/s
Density at 15 °C	EN ISO 3675, EN ISO 12185	860	900	kg/m^3
Flash Point	EN ISO 3679	120	-	°C
Cetane Number	EN ISO 5165	51	-	-
Oxidative Stability, 110 °C	EN 14112	6.0	-	hours
Acid Value	EN 14104	-	0.50	mg KOH/kg
Linolenic Acid Content	EN 14103	-	12	% (m/m)
Ester Content	EN 14103	96.5	-	% (m/m)
Content of FAME with ≥ 4 double bonds		-	1	% (m/m)
Monoglyceride Content	EN 14105	-	0.80	% (m/m)
Diglyceride Content	EN 14105	-	0.20	% (m/m)
Triglyceride Content	EN 14105	-	0.20	% (m/m)
Methanol Content	EN 14110	-	0.20	% (m/m)
Free Glycerine	EN 14105; EN 14106	-	0.02	% (m/m)
Total Glycerine	EN 14105	-	0.25	% (m/m)
Sulfur Content	EN ISO 20846, EN ISO 20884	-	10.0	mg/kg
Sulfated Ash	ISO 3987	-	0.02	% (m/m)
Water Content	EN ISO 12937	-	500	mg/kg
Total Contamination	EN 12662	-	24	mg/kg
Copper Strip Corrosion (3 hours, 50 °C)	EN ISO 2160	-	1	class
Iodine Value	EN 14111	-	120	g I /100 g
Alkali Metals (Na + K)	EN 14108; EN 14109	-	5.0	mg/kg
Earth Alkali Metals (Ca + Mg)	EN 14538	-	5.0	mg/kg
Carbon Residue (in 10 % dist. Residue)	EN ISO 10370	-	0.30	% (m/m)
Phosphorus Content	EN 14107	-	10.0	mg/kg

Table 2.5: Biodiesel Standard ASTM D6751 (United States) (Zahan and Kano, 2018)

Property	Test Method	Limits		Units
		Min	Max	
Kinematic Viscosity, at 40 ℃	D 445	1.9	6.0	mm^2/sec.
Density at 15 ℃	D 1298	820	900	kg/m^3
Flash Point (closed cup)	D 93	93	-	℃
Cloud Point	D 2500	-3	12	℃
Pour Point	ISO 3016	-15	10	℃
Cetane Number	D 613	47	-	-
Oxidation Stability	EN 15751	3	-	hours
Acid Number	D 664	-	0.05	mg KOH/g
Free Glycerin	D 6584	-	0.020	% (m/m)
Total Glycerin	D 6584	-	0.240	% (m/m)
Alcohol Control (one to be met): **1. Methanol Content** **2. Flash Point**	 EN 14110 D 93	 - 130	 0.2 -	 % (m/m) ℃
Sulfur: **S 15 Grade** **S 500 Grade**	 D 5453 D 5453	 - -	 0.0015 0.05	 % (m/m) % (m/m)
Sulfated Ash	D 874	-	0.02	% (m/m)
Water & Sediment	D 2709	-	0.05	% (v/v)
Copper Strip Corrosion	D 130	-	3	No.
Carbon Residue, 100 % Sample	D 4530	-	0.05	% (m/m)
Calcium & Magnesium, Combined	EN 14538	-	5	ppm (µg/g)
Sodium/ Potassium, Combined	EN 14538	-	5	ppm (µg/g)
Phosphorous Content	D 4951	-	0.001	% (m/m)
Distillation-Atmospheric Equivalent Temperature 90 % Recovery	D 1160	-	360	℃
Cold Soak Filtration **For Use in Temperature Under -12 ℃**	D 7501 D 7501	-	360 200	seconds seconds

Malaysian biodiesel quality standard is developed based on European standard. Hence, both standards have almost similar limit values except oxidative stability, monoglyceride, iodine value and phosphorus content. The properties with different values in these standards are boxed with different colours and showed in Table 2.3 and 2.4.

Malaysian standard has higher minimum oxidative stability requirement compared to European's with values 10 hours and 6 hours respectively. Oxidative stability of a biodiesel greatly affecting the storage stability of biodiesel. This is very important as oxidation reaction that will vary the properties of biodiesel may take place if the biodiesel is not oxidative stable enough. Unsaturated fatty acids will undergo oxidation reaction when contact to air that consist of oxygen and form hydrogen peroxides that will be attached to the chain of fatty acid. Larger molecules can be formed with polymerisation activated by hydrogen peroxides (Knothe et al., 2010; Barabas and Todoru, 2011). This will increase the viscosity of biodiesel, increasing pumps or injectors wear. Malaysian standard requires higher minimum oxidative stability to ensure a better quality control of biodiesel. This is important in all year summer Malaysia as elevated temperature promotes the oxidation reaction to occur.

Monoglyceride is an impurity in biodiesel. It will affect the cloud point of biodiesel. Addition of unsaturated monoglyceride may lower the cloud point in certain cases (Chupka et al., 2014). Malaysian standard specified a lower maximum monoglyceride than European standard, meaning less impurities in the biodiesel obtained based on Malaysian standard.

Iodine value also help in indicating the oxidative stability of biodiesel. It measures the amount of total unsaturated component inside biodiesel, thus, defines the tendency of oil to oxidize (Knothe et al., 2010). So, Malaysian standard has a slightly lower maximum iodine value requirement compared to European standard. Maximum phosphorus content required in MS 2008: 2014 is smaller compared to the one stated in EN 14214. Phosphorus is an inorganic contaminant that will influence the catalytic conversion in diesel engines' exhaust system. This will result in more pollutant gases such as sulfur dioxide, carbon monoxides and PM to be generated, causing environmental issue (Lira et al., 2011). Hence, lower phosphorus content tends to reduce the emission of pollutant gases.

Requirements listed in ASTM D6751 also have properties listed in the other two standards with a more general specification since this standard is used for both FAME and FAEE.

2.3 Feasibility Study of Multi-Biodiesel Mixture Production

Biodiesel is the most broadly recognised alternative diesel engines' fuel because of its environmental, strategic and technical advantages. It has reduced toxicity, enhanced biodegradability and improved lubricity of fuel compared to petroleum-based diesel fuel. Good miscibility of biodiesel with conventional diesel fuel consenting blending of these fuels in any share to improve its quality (Candeia et al., 2009; Qi and Lee, 2014).

2.3.1 Blending of Biodiesel

Biodiesel blends are normally represented as "BXX", where "XX" indicating the percentage of biodiesel component in the blend (Nag, 2008). For instance, B10 representing a fuel with 10 % biodiesel and 90 % petrol diesel. Biodiesel can be blended with petrol diesel fuel in various concentration. Biodiesel blends commonly used are B5, B20 and B100. B100 represents solely biodiesel and is usually used to represent the blend stock for biodiesel blends. Biodiesel blend with biodiesel concentration up to 5 % is considered low-level blend. B5 and below can be considered as diesel fuel under ASTM specifications. Quality of B5 can be controlled based on general diesel fuel specifications like ASTM D975. Diesel blends with 2 % to 20 % of biodiesel can be used as fuel in most diesel engines with minor or without modifications. Special handling and equipment modifications may be required for biodiesel blends with more than 20 % of biodiesel (Minnesota Department of Agriculture, 2018).

B6 to B20 are biodiesel blends with 6 to 20 volume percentage of biodiesel, where the rest is made up of light middle or middle distillate diesel fuel (ASTM International, 2009). ASTM D7467 as listed in Table 2-6 is a special biodiesel quality standard where B6 to B20 fuels have to meet before they are being used as fuel in diesel equipment. Addition of biodiesel to petro diesel fuel reduces the amount of pollutant gases being emitted with more complete combustion and improves the lubricity of fuel but increasing the cloud point. Higher cloud point means the fuel will form crystal at higher temperature. This reduces low temperature operability with increase percentage of biodiesel in biodiesel blend. Hence, a balance point needs to be achieved when deciding the percentage of biodiesel in the fuel.

Table 2.6: Biodiesel Blends Standard ASTM D7467 (for B6 to B20) (ASTM International, 2009; Alleman et al., 2016)

Property	Test Method	Limits		Units
		Min	Max	
Acid Number	D 664	-	0.30	mg KOH/g
Viscosity, at 40 °C	D 445	1.9	4.1	mm^2/sec.
Flash Point	D 93	52	-	°C
Cloud Point	D 2500, D 4539, D 6371	Report		°C
Sulfur:				
S 15 Grade	D 5453	-	0.0015	% mass (ppm)
S 500 Grade	D 5453	-	0.05	% mass (ppm)
Physical Distillation, T90	D 86	-	343	°C
Ramsbottom Carbon Residue on 10 % Bottoms	D 524	-	0.35	% mass
Cetane Number	D 613	40	-	-
One of the Following Must be Met:				
1. Cetane Index	D 976-80	40	-	-
2. Aromaticity	D 1319-03	-	35	% volume
Ash Content	D 482	-	0.01	% mass
Water & Sediment	D 2709	-	0.05	% volume
Copper Strip Corrosion, 3 h at 50 °C	D 130	-	3	No.
Phosphorous Content	D 4951	-	0.001	% mass
Biodiesel Content	D 7371	6	20	% volume
Oxidation Stability	EN 14112	6	-	hours
Lubricity, HFRR at 60 °C	D 6079	-	520	Micron (µm)

2.3.2 Significance of Various Biodiesel Blends Properties as Fuel

Different combinations of fuel properties will result in different diesel engine performance. There are various biodiesel blends properties need to be noted when deciding the types of biodiesel and biodiesel-diesel blending ratio used. Some properties influence the performance of a diesel engine while some properties are controlled in order to achieve emission standards listed in the global or national policies.

2.3.2.1 Density

Density is the mass to volume ratio of fuel. In order to ensure proper combustion, density plays an important role as it influences the energy content and air to fuel ratio within the combustion chamber. This is because density is the main property affecting the mass of fuel being delivered by injectors, pumps and injection systems into combustion chamber. A precise amount of fuel into combustion chamber and proper air to fuel ratio in combustion chamber are vital in determining the combustion performance (Saxena, Jawale and Joshipura, 2013; Pratas et al., 2011). In addition, mixing of biodiesel and diesel will be influenced directly by the density. Stratification of mixed biodiesel and diesel will be resulted when the density is extremely high. Other properties of fuel such as viscosity, cetane number and heating value of the fuel are also related to density (Ge, Yoon and Choi, 2017). Thus, density is one of the important properties determining the performance of engine.

2.3.2.2 Viscosity

Viscosity measures a fluid’s resistance to flow resulted from internal friction. This property is important when choosing a suitable fuel as it is influencing the fuel injection system’s performance (Saxena, Jawale and Joshipura, 2013). A biodiesel blend with proper viscosity will provide proper dispersion of fuel into the compressed air. The dispersion patterns for both biodiesel blends with correct viscosity and high viscosity is shown in Figure 2.1. Proper dispersion helps to promote mixing of fuel and air, improve atomization efficiency, shorten ignition time, increase injection pressure, and encourage full combustion of the fuel (Saxena, Jawale and Joshipura, 2013). Proper viscosity resulting in better engine performance.

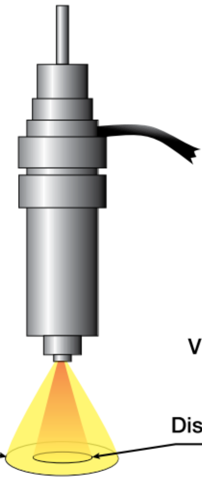

Figure 2.1: Injector Spray Patterns for Diesel with Correct Viscosity and High Viscosity (Renewable Fuels Foundation, 2007)

Fuel with proper viscosity also helps to hinder fuel assembly pump's wear that will be resulted from both extreme case of viscosity. Fuel with too high viscosity leads to incomplete combustion of fuel, increasing formation of carbon deposit in the engine (Ge, Yoon and Choi, 2017). Hence, damaging the pump. For the case where the viscosity of fuel is too low, injection pump will also experience undesired power loss and wear as a result of pump or injector leakage. This undesired outcome may also due to inadequate lubrication of low viscosity fuel to the system. Proper viscosity also improves the lubricity of fuel in diesel engine. A choice of fuel with proper viscosity lies within the range of viscosities specified in the standards will greatly influencing the engine performance.

2.3.2.3 Cetane number

Like octane number for gasoline, cetane number greatly influence the performance of biodiesel blends. Biodiesel blends fuel knocking tendency in a diesel engine can be indicated by cetane number. Several ignition points will be formed as biodiesel blend is atomised and closely mixed with hot compressed air inside the diesel engine. This ensures uniform and early ignition. The hydrocarbon composition of the fuel intimately affecting the ignition rate. Those fuels containing aromatics, cycloaliphatic and olefinic will have longer ignition time compared to fuels comprises of linear paraffinic hydrocarbons, resulting in long delay in ignition. This causes rough engine operation as there will be an extremely rapid pressure increase after combustion. Unwanted products might be formed in such delays as this allows time for unwanted reaction to happen. These undesired products will lead to a very undesirable surge in pressure. Long ignition delays also give rise to uneven combustion and misfiring in a cold engine. Cetane number measures the ignition quality of biodiesel blends based on its paraffinic content (Brownstein, 2015).

Cetane number scale is founded on ignition characteristics of normal C16 paraffin, for instance, n-hexadecane (cetane) and highly branched saturated 2,2,4,4,6,8,8-heptamethlnonane (HMN). High ignition quality cetane has short ignition time, representing 100 on the cetane scale. In contrast, HMN is assigned with a cetane number of 15, being used as the low quality reference fuel since it has long delay period (Brownstein, 2015; Speight, 2011b). Engine size, load variations, and speed, atmospheric conditions and initial conditions varying the requirement of different cetane number. Higher cetane level favours reduction in emission of particulate matter (PM) and nitrogen oxides with better fuel combustion (Renewable Fuels Foundation, 2007).

2.3.2.4 Volatility

Biodiesel blend volatility designate the easiness of fuel vaporisation, affecting the engine’s ease of starting and warm-up performance. This is typically important for diesel engine as biodiesel blend is having lower volatility compared to gasoline, more heat is required to vaporise and initial the combustion reaction of biodiesel blend. Volatility has less effect on economy and power of diesel engine. However, heating values or energy content of biodiesel blend is indirectly related to volatility. Less volatile fuel has higher heating value. Heating value of a biodiesel blend is the heat being released when the fuel is combusted. This will affect the thermal efficiency of power generation (Renewable Fuels Foundation, 2007).

2.3.2.5 Flash Point

Flash point is the lowest temperature at which the volatile matter gives out adequate vapour to be ignitable in air. This helps to characterise the fire hazard so as to achieve the safety requirements in handling and storing diesel fuel (Bacha et al., 2007). Flash point will not affect the engine’s performance, but act as a guard against contamination due to the presence of highly volatile impurities. Example of these impurities is leftover methanol remained in the biodiesel after biodiesel stripping processes (Saxena, Jawale and Joshipura, 2013).

2.3.2.6 Low Temperature Operability

Low temperature operability of fuel is commonly indicated with the pour point and cloud point of fuel. Definition of pour point is the temperature at which the quantity of wax available in the fuel is enough to gel the fuel (Saxena, Jawale and Joshipura, 2013). Cloud point is the temperature at which the smallest observable amount of precipitated wax crystals first seen in the fuel, making the fuel to have hazy or cloudy appearance (Renewable Fuels Foundation, 2007). The presence of precipitated wax will cause thickening of the fuel, eventually leads to clogging of fuel filters and injectors in engines.

2.3.2.7 Sulfur Content

Sulfur content in fuel varies the amount of deposits inside an engine, which is undoubtedly affecting the extent of engine wear. In addition, combustion of fuel containing sulfur produces sulfur dioxide, one of the major culprits leading to acid rain. Sulfur dioxide formed is also harmful for human’s health since it is a moderate lung irritant. PM emissions also can be controlled by controlling the sulfur content in the fuel as sulfate particulars can be formed in the exhaust when the fuel consisting sulfur is combusted (Bacha et al., 2007). Ever restricting air pollution emission regulation forces this property cannot be ignored.

2.3.3 Selection of Biodiesel

There are varieties of biodiesel derived from different feedstocks available in the world. These biodiesels can be produced from feedstocks either from edible or non-edible oils, animal fats or grease. As the biodiesels available in the world are subjected to biodiesel standards, the properties of these biodiesels will not be the main factor in deciding which biodiesel to be used. In fact, the availability and sustainability of biodiesel will be the decision-making factors. The availability of biodiesel greatly influenced by the feedstock available at the location of biodiesel production plant. For example, biodiesel derived from palm oil is abundant in Malaysia since oil palm are available.

Wide use of biodiesel as an alternative of diesel is due to its sustainable characteristic as compared to petroleum derived diesel. Therefore, sustainability of biodiesel used required attention to prevent back-fire from sustainable development. Introduction of biodiesel with oil extracted from oil containing crops initiates deforestation activities as more people deforest an area for them to have oil containing crops plantation which is more profitable. This causes the land used for farming reduces, threatening food security and sustainability. So, choice of biodiesel feedstock is important in ensuring security and sustainability of energy sector (Lim et al., 2019). It also affects environment sustainability if deforestation for oil containing crops plantation continues. Hence, an equilibrium has to be achieved between energy and environment sustainability. Table 2.7 shows the land area needed for oil producing crops growing and the oil productivity attainable by these crops. From table showed below, microalgae used the least land area to produce the highest amount of oil. In contrast, corn only able to yield 172 L ha^{-1} yr^{-1} from 1540 M ha of land growing corn. This again brings up the question of sustainability of corn derived biodiesel.

Table 2.7: Oil Productivity and Land Area Needed for Growing Oil Producing Crops (Kumar and Sharma, 2014).

Crop	**Oil Yield (L ha^{-1} yr^{-1})**	**Land area needed for oil yield (M ha)**
Corn	172	1540
Soybean	446	594
Rapeseed	1190	223
Oil palm	5950	45
Coconut	2689	99
Jatropha	1892	140
Microalgae	136,900	2

2.4 Optimisation of Multi-Biodiesel Mixture Production

Biodiesel as an alternative fuel for diesel engines has received much attention recently, attracted many researchers to study the crop production and conversion processes in biodiesel production. Although these researches are well developed, sustainable biodiesel industry impregnation has yet to be a success due to logistic of the system. For example, most crops are only harvested in a short duration of time yearly though most biodiesel production plants are operated continuously. This forces the manufacturer outsourcing biomass feedstock from other supplier to enable continuous operation. This forms the supply chain of biofuel that connects raw material suppliers, biorefineries, storing facilities, blending stations and consumers together to ensure continuous supply of biomass to conversion units (Awudu and Zhang, 2012; Ba, Prins and Prodhon, 2016). Hence, implementation of an efficient supply chain is necessary. Many researches have been done to develop a suitable model in optimising biofuel supply chain. The optimisation approaches discussed in this section are two of the most used approaches in dealing with complex biodiesel supply chain system.

2.4.1 Fuzzy Optimisation

Fuzzy optimisation is used to deal with system with uncertainties that may be due to limited knowledge and deficiency in understanding related information, leaving the information undefined. Ambiguity is related with the situation where choice between different possibilities remained undetermined. Besides, the possibility of each alternative to occur is unknown due to lack of knowledge and tools (Tang et al., 2004).

Fuzziness in this study is the result of complex characteristic of biomass and difficulty in understanding each biomass species precisely. The fuzziness made this optimisation model an appropriate method in optimising the multi-biodiesel mixture production. This model allowing determination of system configuration, for example, objective coefficient as long as the target values for both footprint and production levels are given (Tan et al., 2009; Borodin et al., 2016).

This model also allowing multiple objectives to be considered when solving the optimisation problem. For instance, fuzzy optimisation with multiple objectives approach has been used in solving the optimisation problem as illustrated in Figure 2.2. The three objectives to be achieved in this problem are:

1. To minimize land area used for biofuel production that threaten food security.
2. To ensure continues supply of fresh water resources to sustain crop growth.
3. To minimize carbon emission during combustion.

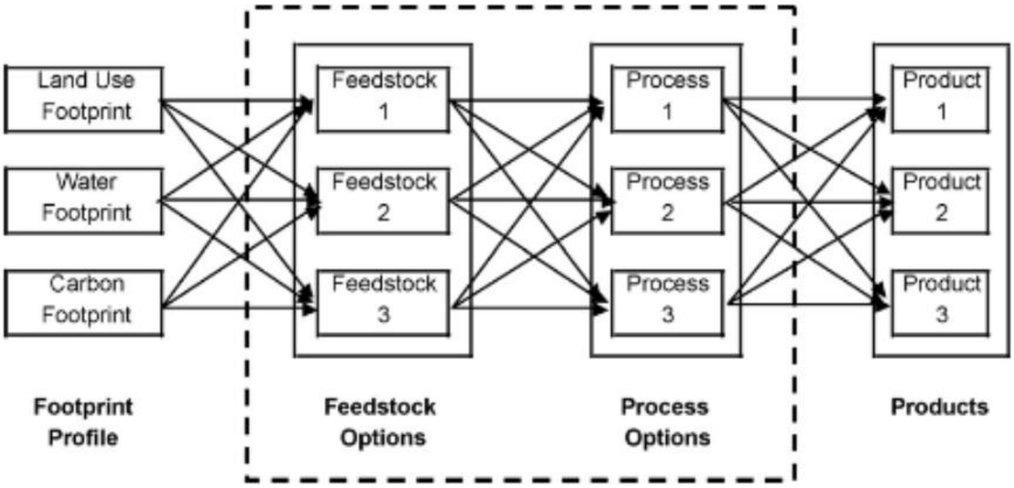

Figure 2.2: Decision Framework for a Bioenergy System Involving Multiple Footprint (Tan et al., 2009)

Fuzzy optimisation with multi-objectives approach allowing a more general consideration of the system as more objectives can be achieved. This is important in biodiesel production due to the ever-restricting environment regulations and stricter quality control of biodiesel blends.

2.4.2 Biomass Element Life Cycle Analysis (BELCA)

This model is an approach proposed by Lim and Lam in their work of optimising biomass supply chain (Lim and Lam, 2016). This is used for potential bio-resources' properties investigation available in the system.

There are several steps listed in this approach in optimising biomass supply chain. Firstly, system life cycle is analysed with the objective to recognise potential biomass consumption within the system especially those biomasses generated within the system as by-products. As an example, empty fruit bunch (EFB) in palm oil extraction plant can be used as biomass in other processes that converts into high value product like fertiliser (Lim and Lam, 2014). However, the biomass within the system has to be classified on an elemental basis before this analysis is carried out. This model helps to study the feasibility of every biomass as alternative resources within the system, trying to fully utilise every biomass. Key element also needs to be identified as it greatly influence properties of a biomass, thus, affecting the biodiesel production and characteristics of multi-biodiesel blend.

Next, element targeting is implemented into the system while constructing a model for biomass supply chain by considering features of biomass element instead of its species form. This is used to safeguard that the optimum solution obtained has taken every underutilised biomass and wastes into account. This model considering both upstream and downstream biomass of the system, providing an overall optimised supply chain (Lim and Lam, 2016).

CHAPTER 3

METHODOLOGY

Inspired by "Biomass Element Life Cycle Analysis (BELCA)" proposed by Lim and Lam in their work of optimising biomass supply chain (Lim and Lam, 2016) that implemented element targeting approach in their model, property targeting (PT) approach will be considered to construct an optimisation model for a diverse biodiesel-diesel blend system. The stricter particular matters (PMs), NO_x, SO_x and many other environment polluting particles emission regulation forced properties of the biodiesel-diesel blend to be important as these properties not only characterise the performance of engine, but also affecting the emission of those environment polluting particles.

An optimum performance of the system in terms of resources material balance and revenue while achieving certain fuel property limits is aimed to be achieved by implementing this model. The model considering a supply chain network of biodiesel produced at various biodiesel production plant, *i* using feedstock supplied from multiple resource locations, *h* to biodiesel-diesel blending facility, *j* and the blends produced will then be sent from the facilities to market, *k* in order to fulfil their respective demands. The biodiesel-diesel blending facilities are located at petroleum refineries. These petroleum refineries are assumed to produce diesel that will be blended with biodiesel to produce biodiesel-diesel blends. The model proposed will be used to maximise the multi-biodiesel supply chain performance based on revenue while achieving certain property limitations. The superstructure of optimisation model using PT approach is illustrated in Figure 3.1.

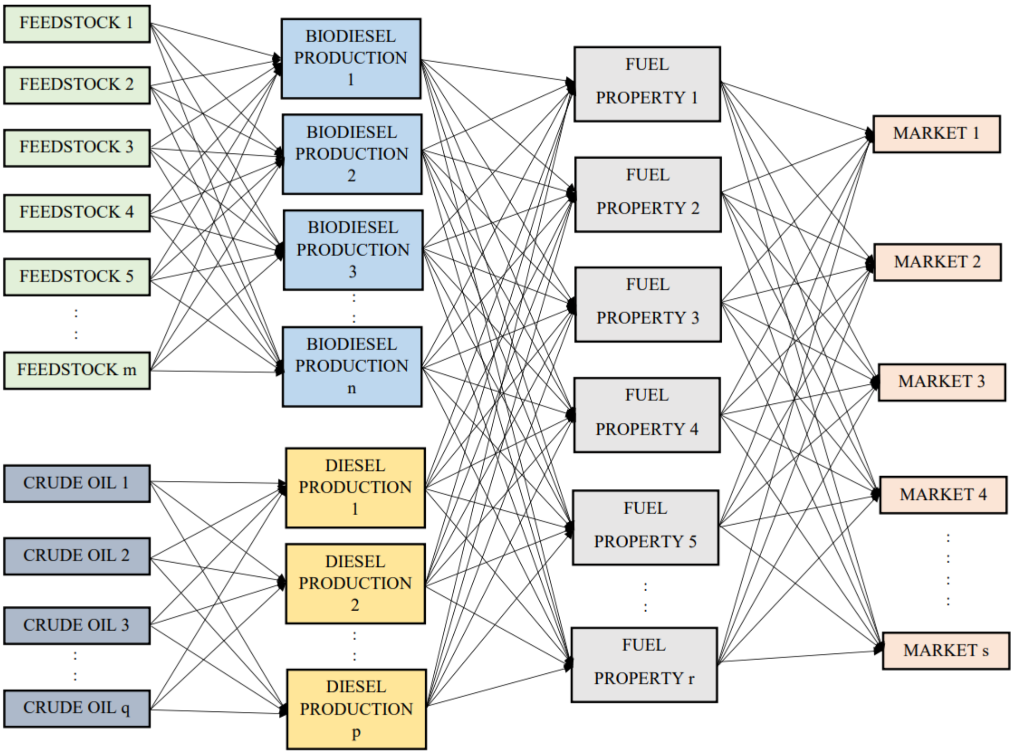

Figure 3.1: Superstructure for the Optimisation Model using PT Approach

3.1 Resources Material Balance Criteria

There are various biodiesel-diesel blend mandates available. The biodiesel-diesel blending facilities, *j* are assumed to be able to produce the blends based on the biodiesel-diesel blend mandates required in market, *k*. The blending facility might be producing the multi biodiesel-diesel blend mandate simultaneously. The material balance accounts for four resources, they are biodiesel production feedstock, biodiesel, crude oil for diesel production and biodiesel-diesel blend. Firstly, the amount of biodiesel-diesel blend produced is required to fulfil demand at market, *k*.

$$\sum_{j=1}^{p} wXX_{j,k} = \text{FPD} \times dmXX_k \qquad (3.1)$$

where,

$wXX_{j,k}$ = Amount of biodiesel-diesel blend with mandate BXX sent from blending facility *j* to market *k*, ML/yr

FPD = Demand of biodiesel-diesel blend fulfilment, %

dm_k = Demand of biodiesel-diesel blend in market *k*, ML/yr

The mandate BXX depends on the requirement of market, *k*. B5-B20 are the common biodiesel-diesel blend mandate where the XX in BXX indicates the percentage of biodiesel in the blend in volume basis. The parameter FPD is introduced as the blending facilities available might not be able to fulfil 100.00 % biodiesel-diesel blend demand required due to limited resources. The total amount of biodiesel-diesel blend with certain biodiesel volume percentage produced at blending facility, *j* is as follows:

$$tbXX_j = \sum_{k=1}^{s} wXX_{j,k} \tag{3.2}$$

where,

$tbXX_j$ = Total amount biodiesel blend BXX produced at blending facility *j*, ML/yr

The total amount of biodiesel used to produce biodiesel-diesel blend BXX can be computed as

$$tb\_bXX_j = \text{BBXXR} \times tbXX_j \tag{3.3}$$

where,

tb_bXX_j = Total amount used to produce biodiesel-diesel blend BXX at blending facility *j*, ML/yr

BBXXR = Volume fraction of biodiesel blended in biodiesel-diesel blend BXX

Total amount used to produce biodiesel-diesel blend BXX at blending facility, *j* can also be computed as the sum of biodiesel amount sent from various biodiesel production plant, *i* to respective blending facility.

$$tb\_bXX_j = \sum_{i=1}^{n} xXX_{i,j} \tag{3.4}$$

where,

$xXX_{i,j}$ = Amount of biodiesel sent from biodiesel production plant *i* to blending facility *j*, ML/yr

In order to fulfil the biodiesel production plant capacity which is in term of mass for this model, the $xXX_{i,j}$ which is in term of volume will be converted to mass before the material balance. The conversion from volume to mass is as below:

$$mXX_{i,j} = 1000xXX_{i,j} \times db_i \tag{3.5}$$

where,

$mXX_{i,j}$ = Amount of biodiesel sent from biodiesel production plant i to blending facility j, MT/yr

db_i = Density of biodiesel produced at biodiesel production plant i in kg/L

Each biodiesel production plant is assumed to be producing only one type of biodiesel. The 1000 in Eq. 3.5 is the factor combining conversion factors for kg to MT and ML to L. The $mXX_{i,j}$ must satisfy the production capacity of biodiesel production plant, i.

$$\sum_{j=1}^{p} mXX_{i,j} \leq \mathrm{bstc_i} \tag{3.6}$$

where,

$\mathrm{bstc_i}$ = Annual biodiesel production capacity at biodiesel production plant i, MT/yr

$\sum_{j=1}^{p} mXX_{i,j}$ = Total amount of biodiesel used for biodiesel-diesel blending at blending facility j regardless of the different biodiesel-diesel blend mandate in MT/yr

Besides fulfilling the biodiesel production plant capacity criteria, the $mXX_{i,j}$ also need to satisfy the feedstock requirement. The amount of feedstock required to produce biodiesel, that is the amount of bio-oil can be calculated using Eq. 3.7 while satisfying Eq. 3.8.

$$fr_i = \left(\frac{100}{cx_i}\right) \times \sum_{j=1}^{p} mXX_{i,j} \quad (3.7)$$

$$\sum_{i=1}^{n} fr_i \times \mathrm{supply}_{\mathrm{i,h}} \leq \mathrm{bftc}_{\mathrm{h}} \quad (3.8)$$

where,

fr_i = Amount of feedstock required for biodiesel produced at biodiesel production plant *i*, MT/yr

cx_i = Conversion of bio-oil to biodiesel at biodiesel production plant *i*, %

$\mathrm{supply}_{\mathrm{i,h}}$ = Supply of feedstock from resource location *h* to biodiesel production plant *i*

$\mathrm{bftc}_{\mathrm{h}}$ = Feedstock available in resource location *h*, MT/yr

The parameter $\mathrm{supply}_{\mathrm{i,h}}$ is used to indicate whether the biodiesel production plant, *i* will obtain feedstock from resource location, *h*. "1" designates that the biodiesel production plant, *i* will obtain feedstock from resource location, *h* and vice versa for "0".

The amount of diesel used for blending with XX amount of biodiesel to produce BXX at blending facility, *j* can be obtained using Eq. 3.9 and the total amount of diesel used at blending facility, *j* must accomplish Eq. 3.10.

$$yXX_j = (1 - \mathrm{BBXXR}) \times tbXX_j \quad (3.9)$$

$$\sum_{j=1}^{p} yXX_j \leq \mathrm{D\_C} \times \mathrm{bd\_cdc}_{\mathrm{j}} \quad (3.10)$$

where,

yXX_j = Amount of diesel blended in BXX at blending facility *j*, ML/yr

$\sum_{j=1}^{p} yXX_j$ = Total amount of diesel used for biodiesel-diesel blending at blending facility *j* regardless of the different biodiesel-diesel blend mandate in ML/yr

D_C = Ratio of amount of diesel obtainable from crude oil to crude oil refined

$\mathrm{bd\_cdc}_{\mathrm{j}}$ = Crude oil distillation capacity at blending facility *j*, ML/yr

D_C is set to be 0.2738 as the petroleum refineries are able to produce around 11 to 12 gallons of ultra-low sulfur diesel from a 42-gallon barrel crude oil generally (U.S. Energy Information Administration (EIA), 2020). The blending facilities are assumed to have blending capacities that are capable to produce biodiesel-diesel blends as long as crude oil distillation capacities limits are satisfied.

3.2 Fuel Properties Criteria

Due to strict quality control of product obtained from biodiesel-diesel blend production, a biodiesel blend quality standard will be chosen to limit the optimisation problem. The requirements specified in the standard will be translated into mathematical formulas that restrict the model.

There are three properties taken into consideration for this model, they are density, kinematic viscosity and cetane number. The biodiesel mixtures are restricted to biodiesel standard ASTM D6751 before they are mixed with diesel and limited by the biodiesel blends standard ASTM D7467 (for B6 to B20). The density of biodiesel mixtures and biodiesel-diesel blends can be computed as

$$Density = \frac{Total\ Mass\ of\ Mixture}{Total\ Volume\ of\ Mixture} \tag{3.11}$$

Density of biodiesel mixture in BXX at blending facility j ($d\_b\_bXX_j$) is constrained with lower and upper limits as follows:

$$d\_b\_bXX_j \geq 0.82 \tag{3.12}$$

$$d\_b\_bXX_j \leq 0.90 \tag{3.13}$$

Density of biodiesel-diesel blends BXX at blending facility j (d_bXX_j) is constrained with lower and upper limits as follows:

$$d\_bXX_j \geq 0.81 \tag{3.14}$$

$$d\_bXX_j \leq 0.87 \tag{3.15}$$

Kay's mixing rule (El-Araby et al., 2018) with $R^2 = 0.9830$ as shown below can be used to estimate kinematic viscosity of biodiesel mixtures and biodiesel-diesel blends:

$$\ln(\mu) = \sum_{m=1}^{n} wt_m \cdot \ln(\mu_m) \qquad (3.16)$$

where,

$\mu =$ Kinematic viscosity of biodiesel mixture or biodiesel-diesel blends obtained at 40 ℃, mm^2/s

μ_m = Kinematic viscosity of component m, mm^2/s

wt_m = Weight fraction of component m

Natural logarithm of biodiesel mixtures' kinematic viscosity in BXX at blending facility j obtained at 40 ℃ ($kv\_b\_bXX_j$) is limited by lower and upper limits as follows:

$$\ln\left(kv\_b\_bXX_j\right) \geq 0.6419 \qquad (3.17)$$

$$\ln\left(kv\_b\_bXX_j\right) \leq 1.792 \qquad (3.18)$$

Natural logarithm of biodiesel-diesel blend BXX's kinematic viscosity at blending facility j obtained at 40 ℃ (kv_bXX_j) is limited by lower and upper limits as follows:

$$\ln\left(kv\_bXX_j\right) \geq 0.6419 \qquad (3.19)$$

$$\ln\left(kv\_bXX_j\right) \leq 1.411 \qquad (3.20)$$

Last but not least, the cetane number of biodiesel mixtures and biodiesel-diesel blends can be estimated using formula (Gopinath et al., 2015):

$$Cetane\ Number = -23.48 + 61.6828\mu - 12.7738\mu^2 + 0.87697\mu^3 \quad (3.21)$$

where,

$\mu =$ Kinematic viscosity of biodiesel mixture or biodiesel-diesel blends obtained at 40 °C, mm^2/s

Cetane number of biodiesel mixture in BXX at blending facility j ($cn\_b\_bXX_j$) need to fulfil the lower limit:

$$cn\_b\_bXX_j \geq 47 \quad (3.22)$$

Cetane number of biodiesel-diesel blends BXX at blending facility j (cn_bXX_j) need to fulfil the lower limit:

$$cn\_bXX_j \geq 40 \quad (3.23)$$

3.3 Supply Chain Performance Optimisation

The supply chain performance will be investigated based on the revenue of biodiesel-diesel blending business obtained. The objective can be formulated into mathematical formula as shown below:

$$z = ts - tfc - tbpc - tbdpc - ttc - twc \qquad (3.24)$$

where,

$z =$ Revenue, RM 10 k/yr

$ts =$ Total sales, RM 10 k/yr

$tfc =$ Total feedstock cost for biodiesel production, RM 10 k/yr

$tbpc =$ Total biodiesel production cost, RM 10 k/yr

$tbdpc =$ Total biodiesel-diesel blend production cost, RM 10 k/yr

$ttc =$ Total truck transportation cost, RM 10 k/yr

$twc =$ Total water transportation cost, RM 10 k/yr

Assumptions made for the objective function are:

- The selling price of biodiesel-diesel blends at market, k are the same within the market.
- The feedstock costs for respective biodiesel are assumed to be inclusive of transportation cost.
- The biodiesel production cost at various biodiesel production plants are assumed to be 12.00 % of their respective feedstock costs since oil feedstock is normally having the highest percentage in total estimated production costs, which is around 88.00 % (Haas et al., 2005).
- The biodiesel-diesel blend production costs at each blending facility are assumed to be inclusive of crude oil cost, refining cost and blending cost.
- Refining cost for 1 litre of crude oil is assumed to be RM 0.18.
- The blending cost for biodiesel-diesel blend at various blending facilities are assumed to be 10.00 % of the biodiesel-diesel blend production costs at each blending facility.
- Truck transportation rate is assumed to be RM 0.99/MT.km.
- Water transportation rate is assumed to be RM 0.27/MT.km.

The model proposed is then simulated and optimised by using General Algebraic Modelling System (GAMS), a high-level mathematical optimisation modelling system. GAMS can be used to solve optimizations and mixed complementarity problems involving linear, mixed integer linear, nonlinear, mixed integer nonlinear models and others.

Case studies will be carried out using the optimisation model constructed to study the effects of percentage fulfilling the demand of market and diversity of biodiesel blended in biodiesel-diesel blend on the properties of blends resulted and revenues.

CHAPTER 4

CASE STUDY, RESULTS AND DISCUSSION

4.1 Case Study

A demonstration case study is created to illustrate the performance of proposed model. Five types of biodiesel will be studied in this case study, they are palm oil, soybean, rapeseed, coconut and recycled cooking oil (RCO). The selection of biodiesels used depends on the sustainability and availability of feedstock. For instance, RCO biodiesel is chosen as this is derived from RCO that can be obtained easily due to increment in food consumption. Besides, utilising RCO as biodiesel feedstock is considered a highly sustainable source as it provides a more environmentally friendly disposal method of large amount RCO instead of dumping RCO as waste. The properties of these biodiesel are tabulated in Table 4.1. The same types of biodiesel are assumed to have the same properties regardless of production plant. The properties of palm oil and coconut biodiesel are extracted from Wakil et al. (2015). Soybean biodiesel properties are extracted from Fabbri et al. (2007), whereas the properties of rapeseed and RCO are extracted from Ge, Yoon and Choi (2017) and Yaakob et al. (2013) respectively. Table 4.2 shows the properties of ultra-low sulfur diesel that will be blended with biodiesel to produce biodiesel-diesel blends. The diesels used are assumed to have the same properties. Biodiesel standard ASTM D6751, diesel standard ASTM D975 and biodiesel blends standard ASTM D7467 are implemented in this case study.

Table 4.1: Properties of Biodiesel Studied

Property	Type of Biodiesel					Limits	
	Palm Oil	Soybean	Rapeseed	Coconut	RCO	Min	Max
Density (kg/L)	0.8951	0.8850	0.8800	0.8605	0.8970	0.82	0.90
Kinematic viscosity (mm^2/s) [at 40 °C]	4.689	4.100	4.290	3.144	5.300	1.9	6.0
Cetane number	52.00	50.90	61.50	59.00	54.00	47	-

Table 4.2: Properties of Diesel

Property	Diesel	Limits		Unit	Reference
		Min	Max		
Density	0.8400	0.81	0.87	kg/L	(VIVA ENERGY AUSTRALIA PTY LTD, 2016)
Kinematic viscosity (at 40 °C)	3.25	1.9	4.1	mm^2/s	
Cetane number	48.00	40	-	-	(Al-Dawody and Bhatti, 2014)

There will be a total of 21 biodiesel production plants under this case study, obtaining bio-oil from various locations. The information of various bio-oil resource locations and biodiesel production plants required for this case study are tabulated in Table 4.3 and Table 4.4 correspondingly. Eight of the blending facilities are set to be petroleum refineries under the company Royal Dutch Shell, mostly located in the United State of America (U.S.A.) and one refinery of Hengyuan Refining Company Berhad that is supplying fuel to the Shell petrol stations in Malaysia. The details of refineries under Shell are extracted from Shell Investors' Handbook 2014-2018 (Shell, 2020) while the additional one refer to HRC Berhad. (2020). These details are listed in Table 4.5. There are four biodiesel-diesel blend markets, being set in Malaysia, Thailand, Indonesia and U.S.A. Table 4.6 listed all the demands for different markets.

Table 4.3: Tabulation of Information for Bio-oil Resource Locations

Type of Bio-oil	Resource Location	Availability (MT/yr)	Cost (RM/MT)	Reference
Palm Oil	Malaysia	19,800,000	2,357.00	(IndexMundi, 2020c; MPOC, 2020)
	Thailand	3,000,000	3,819.29	(IndexMundi, 2020g; krungsri Research, 2016)
Soybean	U.S.A.	11,0200,000	2,694.00	(IndexMundi, 2020h; f)
Rapeseed	Canada	4,225,000	3,434.34	(IndexMundi, 2020a; e)
Coconut	Philippines	1,615,000	3,604.67	(IndexMundi, 2020d; YCHARTS, 2020)
RCO	Malaysia	220,000	1,077.45	(Lee, 2020; EC21 Global B2B Marketplace, 2020)
	Singapore	*1,050,000	1,749.80	(go4WorldBusiness, 2020)
	Thailand	*10,000	1,740.00	(WALAILAK KEERATIPIPATPONG, 2020)

*The availability of recycled cooking oil in Singapore and Thailand are assumed from recycled cooking oil biodiesel production plant in the countries. These assumptions are made as people consume large amount of cooking oil, biodiesel production plant capacity will be a greater limiting factor for RCO biodiesel production for the model.

Table 4.4: Tabulation of Information for Biodiesel Production Plants

Type of Biodiesel	Country	No.	Biodiesel Production Plant	Plant Capacity (MT/yr)	Conversion (%, from bio-oil to biodiesel)	Reference
Palm Oil	Malaysia	A1.	Vance Bioenergy Sdn. Bhd.	300,000	93.60	(New Energy Foundation, 2020; Alkabbashi et al., 2009)
		A2.	YPJ Palm International Sdn. Bhd.	60,000		
		A3.	Carotino Sdn. Bhd.	180,000		
		A4.	Malaysian Vegetable Oil Refinery Sdn. Bhd.	100,000		
		A5.	PGEO Bioproducts Sdn.Bhd.	100,000		
		A6.	Nexsol(Malaysia) Sdn. Bhd.	100,000		
	Thailand	A7.	Global Green Chemicals PCL.	291,611		(Narin Tunpaiboon, n.d.; Alkabbashi et al., 2009)
		A8.	New Biodiesel Co., Ltd.	283,503		
Soybean	U.S.A.	A9.	World Energy Houston, TX	301,508	98.30	(Biodiesel Magazine, 2020b; Colombo et al., 2019)
		A10.	World Energy Natchez, MS	241,206		
		A11.	REG Grays Harbor LLC	335,009		
		A12.	RBF Port Neches LLC	603,016		

Table 4.4 (Continued)

Type of Biodiesel	Country	No.	Biodiesel Production Plant	Plant Capacity (MT/yr)	Conversion (%, from bio-oil to biodiesel)	Reference
Rapeseed	Canada	A13.	World Energy Hamilton, ON	224,456	97.40	(Biodiesel Magazine, 2020a; Encinar et al., 2018)
Coconut	Philippines	A14.	Chemrez Technologies, Inc.	72,282	90.00	(Philippines' Department of Energy, 2020; Tupufia and A, 2012)
		A15.	Tantuco Enterprises, Inc.	77,445		
		A16.	Phil. Biochem Products, Inc.	68,840		
		A17.	Bio Renewable Energy Ventures Inc.	129,075		
		A18.	Pure Essence International, Inc.	61,956		
RCO	Malaysia	A19.	FatHopes	204,000	97.00	(Lee, 2020; Elkady, Zaatout and Balbaa, 2015)
	Singapore	A20.	Neste Singapore	1,000,000		(Neste, 2020; Elkady, Zaatout and Balbaa, 2015)
	Thailand	A21.	Bio Synergy Co., Ltd.	8,880		(Narin Tunpaiboon, n.d.; Elkady, Zaatout and Balbaa, 2015)

Table 4.5: Tabulation of Information for Refineries Used as Blending Facilities

Country	No.	Blending Facility	Crude Distillation Capacity (ML/yr)	Crude Oil Cost (RM/ L)
Singapore	BF1.	Pulau Bukom	24,292	0.88
United States of America	BF2.	Deer Park, Texas	16,369	0.88
	BF3.	Convent, Louisiana	12,539	
	BF4.	Norco, Louisiana	12,015	
	BF5.	Martinez, California	7,555	
	BF6.	Puget Sound, Washington	7,188	
Japan	BF7.	Yokkaichi	12,277	0.87
Malaysia	BF8.	Hengyuan Refining Company Berhad	8,185	0.87
Philippines	BF9.	Tabangao	5,037	0.89

*Crude oil costs are retrieved from IndexMundi, (2020b).

Table 4.6: Demand of Biodiesel-Diesel Blends in Different Markets

Market	Biodiesel Mandate	Demand (ML/yr)	Selling Price (RM/ L)	Reference
Malaysia	B10	8,852	1.46	(GANESHWARAN KANA, 2019; Caltex Malaysia, 2020)
Thailand	B10	10,950	2.27	(Bioenergy International, 2020; Shell Thailand, 2020)
Indonesia	B20	6,200	2.71	(The Jakarta Post, 2018; Shell Indonesia, 2020)
U.S.A.	B20	9,199	3.25	(Milne, 2019; Bourbon and Science, 2018)

There are two types of transportation for delivering biodiesels to biodiesel-diesel blending plants and biodiesel-diesel blends to market, they are truck and ship. The distance travelled by truck and ship from biodiesel production plants to blending facilities are tabulated in Table 4.7 and Table 4.8. The distance travelled by truck and ship from blending facilities to markets are tabulated in Table 4.9.

Table 4.7: Tabulation of Distance Travelled by Truck and Ship from Biodiesel Production Plants to Blending Facilities BF1-BF5

Blending Facility	**BF1.**		**BF2.**		**BF3.**		**BF4.**		**BF5.**	
Biodiesel Production Plant	**Travelled Distance (km)**		**Travelled Distance (km)**		**Travelled Distance (km)**		**Travelled Distance (km)**		**Travelled Distance (km)**	
	By Truck	By Ship	By Truck	By Ship	By Truck	By Ship	By Truck	By Ship	By Truck	By Ship
A1.	6.00	28.19	19.77	16,014.20	23.96	16,181.51	67.89	16,181.51	44.88	13,577.39
A2.	13.30	28.19	27.07	16,014.20	31.26	16,181.51	75.19	16,181.51	52.18	13,577.39
A3.	4.00	28.19	17.77	16,014.20	21.96	16,181.51	65.89	16,181.51	42.88	13,577.39
A4.	4.10	28.19	17.87	16,014.20	22.06	16,181.51	65.99	16,181.51	42.98	13,577.39
A5.	3.20	28.19	16.97	16,014.20	21.16	16,181.51	65.09	16,181.51	42.08	13,577.39
A6.	12.50	28.19	26.27	16,014.20	30.46	16,181.51	74.39	16,181.51	51.38	13,577.39
A7.	63.50	1,353.60	77.27	14,966.58	81.46	15,061.73	125.39	15,061.73	102.38	12,789.68
A8.	190.00	1,131.32	203.77	15,367.70	207.96	15,449.79	251.89	15,449.79	228.88	13,210.33
A9.	28.07	16,042.36	11.10	0.00	469.93	0.00	516.60	0.00	3,104.43	0.00
A10.	3.45	16,034.23	497.29	0.00	197.95	0.00	244.62	0.00	3,382.84	0.00
A11.	41.27	12,927.25	3,852.77	0.00	4,184.29	0.00	4,230.97	0.00	1,213.45	0.00

Table 4.7 (Continued)

Blending Facility	**BF1.**		**BF2.**		**BF3.**		**BF4.**		**BF5.**	
Biodiesel Production Plant	**Travelled Distance (km)**		**Travelled Distance (km)**		**Travelled Distance (km)**		**Travelled Distance (km)**		**Travelled Distance (km)**	
	By Truck	By Ship	By Truck	By Ship	By Truck	By Ship	By Truck	By Ship	By Truck	By Ship
A12.	17.13	16,080.36	135.67	0.00	339.57	0.00	386.24	0.00	3,233.17	0.00
A13.	3.20	15,054.74	2,417.00	0.00	2,114.00	0.00	3,303.98	0.00	4,136.00	0.00
A14.	20.70	2,401.15	34.47	13,763.82	38.66	13,997.69	82.59	13,997.69	59.58	11,226.41
A15.	13.00	2,401.15	26.77	13,763.82	30.96	13,997.69	74.89	13,997.69	51.88	11,226.41
A16.	25.70	2,401.15	39.47	13,763.82	43.66	13,997.69	87.59	13,997.69	64.58	11,226.41
A17.	4.10	2,449.43	17.87	14,015.12	22.06	14,293.38	65.99	14,293.38	42.98	11,391.72
A18.	22.00	2,401.15	35.77	13,763.82	39.96	13,997.69	83.89	13,997.69	60.88	11,226.41
A19.	41.20	330.44	54.97	15,984.26	59.16	16,118.78	103.09	16,118.78	80.08	13,631.99
A20.	8.90	18.24	22.67	16,049.41	26.86	16,214.80	70.79	16,214.80	47.78	13,615.83
A21.	247.00	1,430.30	260.77	14,910.40	264.96	15,001.13	308.89	15,001.13	285.88	12,752.13

Table 4.8: Tabulation of Distance Travelled by Truck and Ship from Biodiesel Production Plants to Blending Facilities BF6-BF9

Blending Facility	**BF6.**		**BF7.**		**BF8.**		**BF9.**	
Biodiesel Production Plant	**Travelled Distance (km)**		**Travelled Distance (km)**		**Travelled Distance (km)**		**Travelled Distance (km)**	
	By Truck	By Ship	By Truck	By Ship	By Truck	By Ship	By Truck	By Ship
A1.	13.33	12,887.07	15.40	5,035.11	304.00	0.00	11.40	2,330.31
A2.	20.63	12,887.07	22.70	5,035.11	323.00	0.00	18.70	2,330.31
A3.	11.33	12,887.07	13.40	5,035.11	302.00	0.00	9.40	2,330.31
A4.	11.43	12,887.07	13.50	5,035.11	307.00	0.00	9.50	2,330.31
A5.	10.53	12,887.07	12.60	5,035.11	307.00	0.00	8.60	2,330.31
A6.	19.83	12,887.07	21.90	5,035.11	324.00	0.00	17.90	2,330.31
A7.	70.83	11,940.00	72.90	4,334.16	1,729.00	0.00	68.90	2,180.97
A8.	197.33	12,356.57	199.40	4,744.77	972.00	0.00	195.40	2,475.83
A9.	3,851.16	0.00	37.47	11,019.76	27.17	16,012.71	33.47	13,829.36
A10.	4,068.42	0.00	12.85	11,076.43	2.55	15,977.18	8.85	13,901.72
A11.	300.95	0.00	50.67	7,875.52	40.37	12,928.87	46.67	10,678.16

Table 4.8 (Continued)

Blending Facility	**BF6.**		**BF7.**		**BF8.**		**BF9.**	
Biodiesel Production Plant	**Travelled Distance (km)**		**Travelled Distance (km)**		**Travelled Distance (km)**		**Travelled Distance (km)**	
	By Truck	By Ship	By Truck	By Ship	By Truck	By Ship	By Truck	By Ship
A12.	3,979.91	0.00	26.53	11,070.36	16.23	16,043.89	22.53	13,884.64
A13.	4,172.00	0.00	12.60	10,563.86	2.30	14,920.76	8.60	13,327.17
A14.	28.03	10,624.72	30.10	2,756.10	19.80	2,491.74	113.00	0.00
A15.	20.33	10,624.72	22.40	2,756.10	12.10	2,491.74	112.00	0.00
A16.	33.03	10,624.72	35.10	2,756.10	24.80	2,491.74	93.60	0.00
A17.	11.43	10,917.57	13.50	3,185.32	3.20	2,613.64	1,331.00	0.00
A18.	29.33	10,624.72	31.40	2,756.10	21.10	2,491.74	108.00	0.00
A19.	48.53	12,885.68	50.60	5,082.04	102.00	0.00	46.60	2,468.09
A20.	16.23	12,923.34	18.30	5,072.91	310.00	0.00	14.30	2,369.74
A21.	254.33	11,893.35	256.40	4,313.62	1,811.00	0.00	252.40	2,209.27

Table 4.9: Tabulation of Distance Travelled by Truck and Ship from Blending Facilities to Markets

Biodiesel Production Plant	**Malaysia**		**Thailand**		**Indonesia**		**United States**	
Blending Facility	**Travelled Distance (km)**		**Travelled Distance (km)**		**Travelled Distance (km)**		**Travelled Distance (km)**	
	By Truck	By Ship	By Truck	By Ship	By Truck	By Ship	By Truck	By Ship
BF1.	2.00	330.45	2.00	1,357.97	2.00	883.57	2.00	14,151.67
BF2.	15.45	15,984.56	15.45	14,961.39	15.45	16,532.11	15.77	-
BF3.	20.44	16,119.30	20.44	15,056.87	20.44	16,771.45	463.49	-
BF4.	20.44	16,119.30	20.44	15,056.87	20.44	16,771.45	510.16	-
BF5.	40.88	13,632.03	40.88	12,784.18	40.88	13,940.59	638.91	-
BF6.	9.33	12,885.60	9.33	11,934.44	9.33	13,397.11	172.20	-
BF7.	11.70	5,082.10	11.70	4,329.01	11.70	5,527.48	11.70	9,107.83
BF8.	100.00	-	1,676.00	-	1.10	1,111.34	1.10	14,197.33
BF9.	7.40	2,466.96	7.40	2,178.40	7.40	2,705.24	7.40	11,816.37

These data are inserted into the proposed model and the model is run using GAMS. The case is solved in different scenarios, starting with 50.00 % of the demands listed in Table 4.6. An increment of 15.00 % is then added on 50.00 % to 65.00 % and further increased with the same increment to demand fulfilment of 95.00 %. This is aimed to study the effect of fluctuation in demand toward the performance of the supply chain. Demand fulfilment of 100.0 % is not considered as no feasible solution is obtained. This is because the limited amount of biodiesel produced by all the biodiesel production plants is unable to support the biodiesel-diesel blend demand requested by all market at 100.0 % demand fulfilment. Table 4.10 shows the summary of all scenarios studied for this case. The results obtained will be tabulated and discussed in the next section.

Table 4.10: Summary of Scenarios Studied in This Case

Scenario	**Demand Fulfilment (%)**
1	50.00
2	65.00
3	80.00
4	95.00

4.2 Results and Discussions

The proposed model is run with demand fulfilment of 50.00 %. The details of biodiesel-diesel blends produced at different blending facilities obtained at demand fulfilment of 50.00 % are tabulated in Table 4.11. The table only tabulated blends' details of those operating facilities.

At demand fulfilment of 50.00 %, not all the bending facilities are in operation as observed from Table 4.11. Those blending facilities located in Asia like Shell Pulau Bukom in Singapore, Shell Yokkaichi in Japan, Hengyuan in Malaysia, and Shell Tabangao in Philippines are operating, to cope with large demand in Asia markets as listed in Table 4.6. Blending facility Shell Deer Park, U.S.A. is the only American facility that is producing biodiesel-diesel blend, typically B20 at demand fulfilment of 50.00 % since this facility alone is able to satisfy the demand of B20 in the U.S.A, which is 50.00 % of 9,199 ML/yr. The amount of blend being delivered from blending facilities to markets at demand fulfilment of 50.00 % are converted to percentage and showed in Figure 4.1. The amount of biodiesel-diesel blend produced at a blending facility will affect the supply pattern of blends to markets. For example, Malaysia is getting B10 supplies from Shell Pulau Bukom and Hengyuan because Hengyuan is unable to fulfil all the demand in Malaysia.

As noted from Table 4.11, blending facilities Shell Pulau Bukom and Hengyuan have full biodiesel supplies from production plants producing biodiesel from RCO, blending facility Shell Deer Park is obtaining biodiesel only from soybean biodiesel production plants while blending facilities Shell Yokkaichi and Shell Tabangao are blending multiple types of biodiesel with diesel. The blending facilities utilise biodiesel from cheaper feedstock or from biodiesel production plants located nearby the blending facilities. The biodiesel mixture blended can be from same source or different sources, greatly depending on the availability of biodiesel, price of feedstock, properties of biodiesel and distance between the production plant and blending facilities. Appropriate choice of biodiesel source helps to minimise the costs, maximising revenue while satisfying the ASTM standards.

Table 4.11: Tabulation of Details of Biodiesel-Diesel Blends Produced at Different Blending Facilities at Demand Fulfilment of 50.00 %

Blending Facility	**Biodiesel Blends**	**Total Blend Production (ML/yr)**	**Percentage of Multi-Biodiesel in Blend (%)**					**Density (kg/L)**	**Kinematic Viscosity [at 40 °C] (mm2/s)**	**Cetane Number**
			Palm Oil	Soybean	Rapeseed	Coconut	RCO			
Pulau Bukom	B10	4634.61	0.00	0.00	0.00	0.00	100.00	0.8460	3.425	73.17
	B20	3100.00	0.00	0.00	0.00	0.00	100.00	0.8510	3.604	73.96
Deer Park	B10	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
	B20	4599.50	0.00	100.00	0.00	0.00	0.00	0.8490	3.411	73.11
Yokkaichi	B10	1243.96	92.04	0.00	0.00	0.00	7.96	0.8420	3.380	72.93
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Hengyuan	B10	2490.06	0.00	0.00	0.00	0.00	100.00	0.8460	3.425	73.17
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Tabangao	B10	1532.37	93.61	0.00	0.00	0.00	6.39	0.8420	3.377	72.93
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-

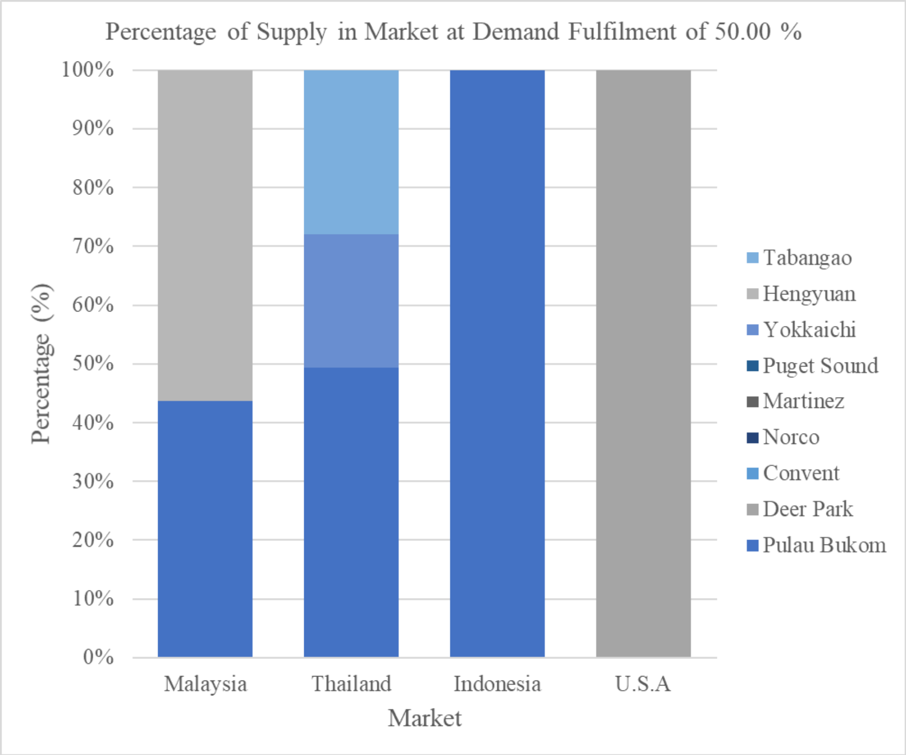

Figure 4.1: Percentage of Supply in Market at Demand Fulfilment of 50.00 %

Table 4.12 shows the sales, costs and revenues obtained at different demand fulfilment.

Table 4.12: Tabulation of Sales, Costs and Revenues at Demand Fulfilment of 50.00 %

Total Sales (RM 10 k/yr)	4223958.50
Total Feedstock Cost (RM 10 k/yr)	483562.37
Total Biodiesel Production Cost (RM 10 k/yr)	64098.83
Total Biodiesel-Diesel Blend Production Cost (RM 10 k/yr)	647.47
Total Truck Transport Cost (RM 10 k/yr)	41603.77
Total Water Transport Cost (RM 10 k/yr)	382811.79
Revenue (RM 10 k/yr)	3251234.29

At demand fulfilment of 50.00 %, the total sales obtained is RM 42239585.00 k/yr with maximum revenue of RM 32512342.90 k/yr as shown in Table 4.12. Total costs payable is RM 9727242.10 k/yr, where total feedstock cost contributes the most followed by total water transport cost, total biodiesel production cost, total truck transport cost and total biodiesel-diesel blend production cost. Total feedstock cost for biodiesel production and transportation costs are the major costs for this supply chain.

4.3 Evaluate Fluctuation of Demand

The proposed model is also run with demand fulfilment of 65.00 %, 80.00 % and 95.00 % to evaluate the effects of fluctuated demand on the pattern and performance of supply chain. Demand fulfilment at 100.0 % cannot be accomplished in this case study as no feasible solution is obtained. This is due to limited capacities of biodiesel production plants set. The total amount of biodiesel produced by all the plants are not able to fulfil markets' demand at 100.0 % fulfilment.

The details of biodiesel-diesel blends produced by different blending facilities at 65.00 %, 80.00 % and 95.00 % of demand fulfilments are tabulated in Table 4.13, Table 4.14 and Table 4.15 correspondingly. These tables only tabulated blends' details of those operating facilities.

As observed from Table 4.11 and Table 4.13 to Table 4.15, the blending facilities acquired biodiesel from biodiesel production plant nearby before they are forced to search for other option that is further away from the blending facilities. Shell Pulau Bukom in Singapore, Shell Yokkaichi in Japan, Hengyuan Refining Company Berhad in Malaysia and Shell Tabangao located in Philippines mainly blend biodiesel from palm oil biodiesel and recycled cooking oil biodiesel as these biodiesels are obtainable at cheaper cost. Since feedstock cost for biodiesel production contributes the most in total biodiesel production, feedstock cost will be one of the main factors influencing the supply chain pattern and performance.

From Table 4.3, palm oil biodiesel producers in Malaysia can obtain palm oil at RM 2,357.00/MT while Asia biodiesel producers producing biodiesel from RCO able to get RCO at a maximum price of RM 1749.80/MT. These prices cause the blending facilities in Asia to buy biodiesel from these biodiesel suppliers as they are more affordable compared to palm oil biodiesel suppliers from Thailand and coconut biodiesel suppliers from Philippines. The high price of coconut oil in Philippines even causes Shell Tabangao in Philippines to search for biodiesel from other countries like Malaysia that is offering biodiesel feedstock at lower price. High price of palm oil in Thailand and coconut oil in Philippines causes biodiesel suppliers using these feedstocks to be the last options that will only be chosen when biodiesel supplies from lower price biodiesel suppliers cannot satisfy the demand in the markets. For example, coconut biodiesel is blended in biodiesel-diesel blend B20 at Shell Yokkaichi when the demand fulfilment reaches 95.00 %.

Like those blending facilities in Asia, blending facilities located in U.S.A. have biodiesel suppliers mainly from U.S.A. which is soybean biodiesel producers as soybean oil can be obtained at RM 2,694.00/MT before they have biodiesel sourced from U.S.A.'s neighbour Canada that is producing biodiesel from rapeseed oil. This is because rapeseed oil is more expensive, which is being sold at RM 3,434.34/MT. When demand fulfilment passed 80.00 %, blending facilities in U.S.A started to have biodiesels from Asia biodiesel suppliers in order to fulfil the high demand in markets as shown in Table 4.14.

As demand fulfilment increases, blending facilities have to obtain biodiesel from multiple sources and types as the amount of biodiesel available is limited by the capacities of biodiesel production plants set in this case study. The use of multiple biodiesels, especially different types of biodiesel in biodiesel-diesel blending alters the properties of the blends but the influences are small. For instance, properties of B20 produced by Shell Pulau Bukom at different demand fulfilment change slightly as the percentages of RCO in B20 reduce when demand fulfilment rises.

As noted from Table 4.11 and Table 4.13 to Table 4.15, the biodiesel mixtures in both B10 and B20 blends comprised mainly of RCO biodiesel are having densities of higher values compared to others because biodiesel produced from RCO has density of 0.8970 kg/L. Besides, the biodiesel mixtures in both B10 and B20 blends primarily contain RCO biodiesel are also having larger kinematic viscosities and cetane numbers than other biodiesel mixtures since RCO biodiesel has the highest kinematic viscosity among the biodiesels studied. However, since both multi-biodiesel mixtures and biodiesel-diesel blends produced by all the blending facilities satisfied the ASTM standards, the use of multi-biodiesel mixture in biodiesel-diesel blending will not be a problem and is applicable, especially when there is limited source of biodiesel.

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Table 4.13: Tabulation of Details of Biodiesel-Diesel Blends Produced at Different Blending Facilities at Demand Fulfilment of 65.00 %

Blending Facility	**Biodiesel Blends**	**Total Blend Production (ML/yr)**	**Percentage of Multi-Biodiesel in Blend (%)**					**Density (kg/L)**	**Kinematic Viscosity [at 40 °C] (mm2/s)**	**Cetane Number**
			Palm Oil	Soybean	Rapeseed	Coconut	RCO			
Pulau Bukom	B10	3,807.94	0.00	0.00	0.00	0.00	100.00	0.8460	3.425	73.17
	B20	4,030.00	8.93	0.00	0.00	0.00	91.07	0.8510	3.597	73.93
Deer Park	B10	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
	B20	5,602.29	0.00	100.00	0.00	0.00	0.00	0.8490	3.411	73.11
Puget Sound	B10	1,305.99	0.00	100.00	0.00	0.00	0.00	0.8440	3.330	72.67
	B20	377.06	0.00	100.00	0.00	0.00	0.00	0.8490	3.411	73.11
Yokkaichi	B10	3,734.94	97.35	0.00	0.00	0.00	2.65	0.8420	3.377	72.92
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Hengyuan	B10	2,490.06	8.67	0.00	0.00	0.00	91.33	0.8450	3.421	73.15
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Tabangao	B10	1,532.37	100.00	0.00	0.00	0.00	0.00	0.8420	3.374	72.91
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-

Table 4.14: Tabulation of Details of Biodiesel-Diesel Blends Produced at Different Blending Facilities at Demand Fulfilment of 80.00 %

Blending Facility	**Biodiesel Blends**	**Total Blend Production (ML/yr)**	**Percentage of Multi-Biodiesel in Blend (%)**					**Density (kg/L)**	**Kinematic Viscosity [at 40 °C] (mm2/s)**	**Cetane Number**
			Palm Oil	Soybean	Rapeseed	Coconut	RCO			
Pulau Bukom	B10	2,981.28	0.00	0.00	0.00	0.00	100.00	0.8460	3.425	73.17
	B20	4,960.00	17.67	0.00	0.00	0.00	82.33	0.8500	3.586	73.89
Deer Park	B10	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
	B20	5,602.29	0.00	100.00	0.00	0.00	0.00	0.8490	3.411	73.11
Convent	B10	617.81	0.00	0.00	100.00	0.00	0.00	0.8440	3.347	72.75
	B20	1,756.91	0.00	49.56	50.44	0.00	0.00	0.8480	3.428	73.19
Martinez	B10	2,298.40	30.44	69.56	0.00	0.00	0.00	0.8440	3.343	72.74
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Puget Sound	B10	2,186.75	0.00	100.00	0.00	0.00	0.00	0.8440	3.330	72.67
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Yokkaichi	B10	3,734.94	97.35	0.00	0.00	0.00	2.65	0.8420	3.377	72.92
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-

Table 4.14 (Continued)

Blending Facility	**Biodiesel Blends**	**Total Blend Production (ML/yr)**	**Percentage of Multi-Biodiesel in Blend (%)**					**Density (kg/L)**	**Kinematic Viscosity [at 40 °C] (mm2/s)**	**Cetane Number**
			Palm Oil	Soybean	Rapeseed	Coconut	RCO			
Hengyuan	B10	2,490.06	8.67	0.00	0.00	0.00	91.33	0.8450	3.421	73.15
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Tabangao	B10	1,532.37	100.00	0.00	0.00	0.00	0.00	0.8420	3.374	72.91
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-

Table 4.15: Tabulation of Details of Biodiesel-Diesel Blends Produced at Different Blending Facilities at Demand Fulfilment of 95.00 %

Blending Facility	**Biodiesel Blends**	**Total Blend Production (ML/yr)**	**Percentage of Multi-Biodiesel in Blend (%)**					**Density (kg/L)**	**Kinematic Viscosity [at 40 °C] (mm2/s)**	**Cetane Number**
			Palm Oil	Soybean	Rapeseed	Coconut	RCO			
Pulau Bukom	B10	2,154.61	0.00	0.00	0.00	0.00	100.00	0.8460	3.425	73.17
	B20	5,890.00	23.65	0.00	0.00	0.00	76.35	0.8500	3.579	73.87
Deer Park	B10	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
	B20	5,602.29	0.76	91.22	0.00	7.14	0.88	0.8490	3.401	73.05
Convent	B10	1,026.41	100.00	0.00	0.00	0.00	0.00	0.8420	3.374	72.91
	B20	3,136.76	15.90	43.44	40.66	0.00	0.00	0.8480	3.438	73.24
Norco	B10	3,388.37	100.00	0.00	0.00	0.00	0.00	0.8420	3.374	72.91
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Martinez	B10	2,298.40	0.00	69.56	0.00	30.44	0.00	0.8440	3.304	72.50
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Puget Sound	B10	2,186.75	0.00	100.00	0.00	0.00	0.00	0.8440	3.330	72.67
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-

Table 4.15 (Continued)

Blending Facility	**Biodiesel Blends**	**Total Blend Production (ML/yr)**	**Percentage of Multi-Biodiesel in Blend (%)**					**Density (kg/L)**	**Kinematic Viscosity [at 40 °C] (mm2/s)**	**Cetane Number**
			Palm Oil	Soybean	Rapeseed	Coconut	RCO			
Yokkaichi	B10	3,734.94	12.72	0.00	0.00	87.28	0.00	0.8420	3.258	72.21
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Hengyuan	B10	2,490.06	8.67	0.00	0.00	0.00	91.33	0.8450	3.421	73.15
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Tabangao	B10	1,532.37	100.00	0.00	0.00	0.00	0.00	0.8420	3.374	72.91
	B20	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-

Figure 4.2 to Figure 4.4 showed the percentage of biodiesel-diesel blend being supplied from each blending facility to fulfil demand in the markets at demand fulfilment of 65.00 %, 80.00 % and 90.00 % respectively. From Table 4.6, the demand in Thailand is the highest followed by U.S.A. and Malaysia. Indonesia is having the least demand.

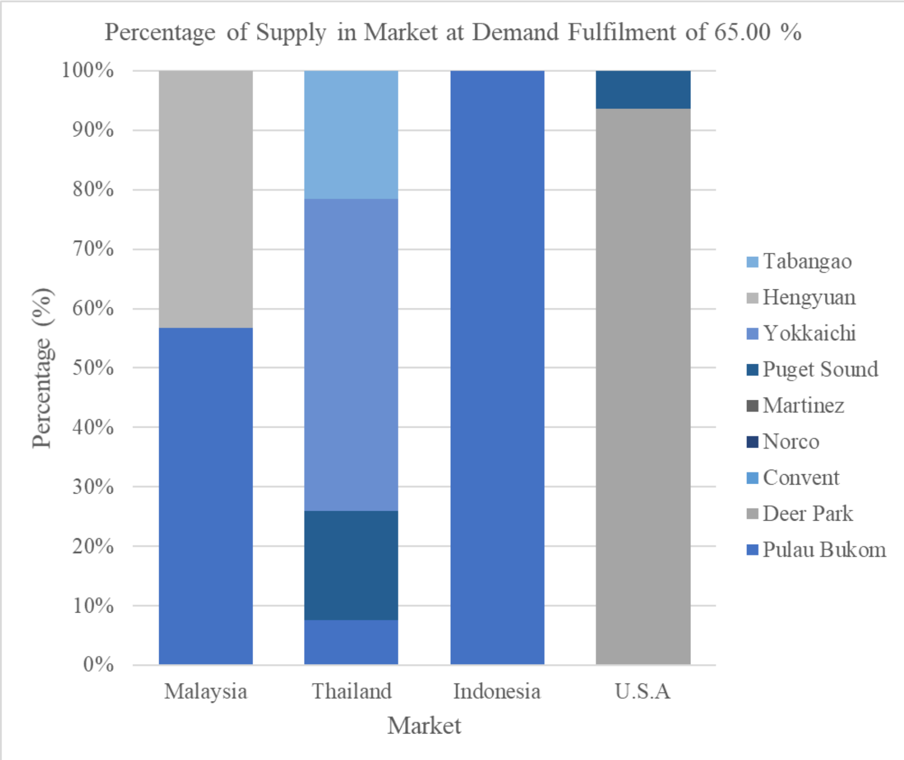

Figure 4.2: Percentage of Supply in Market at Demand Fulfilment of 65.00 %

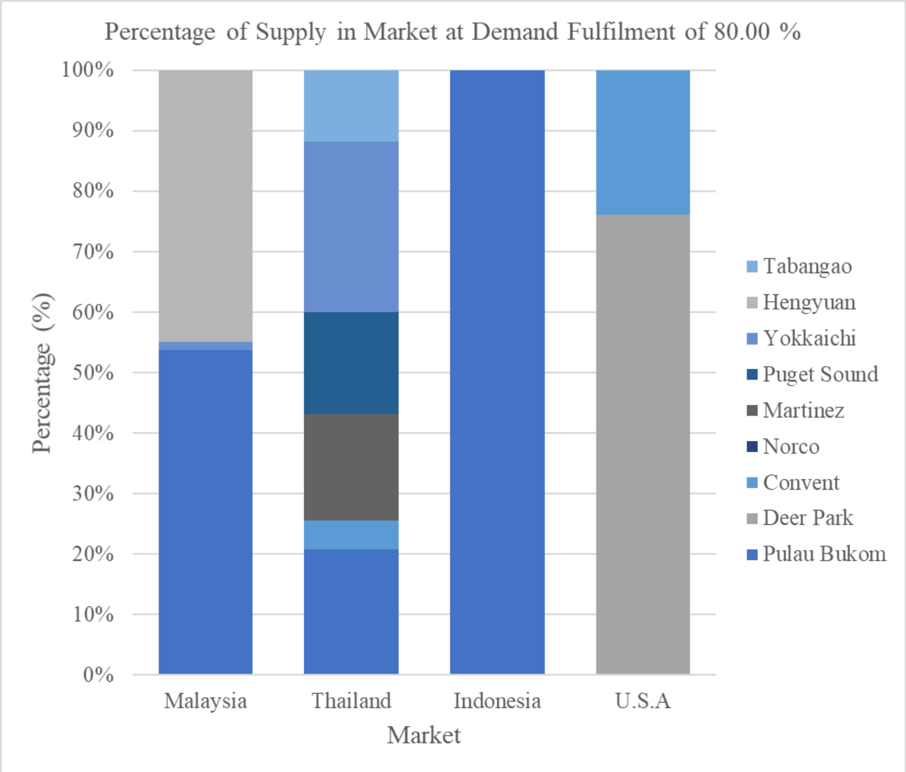

Figure 4.3: Percentage of Supply in Market at Demand Fulfilment of 80.00 %

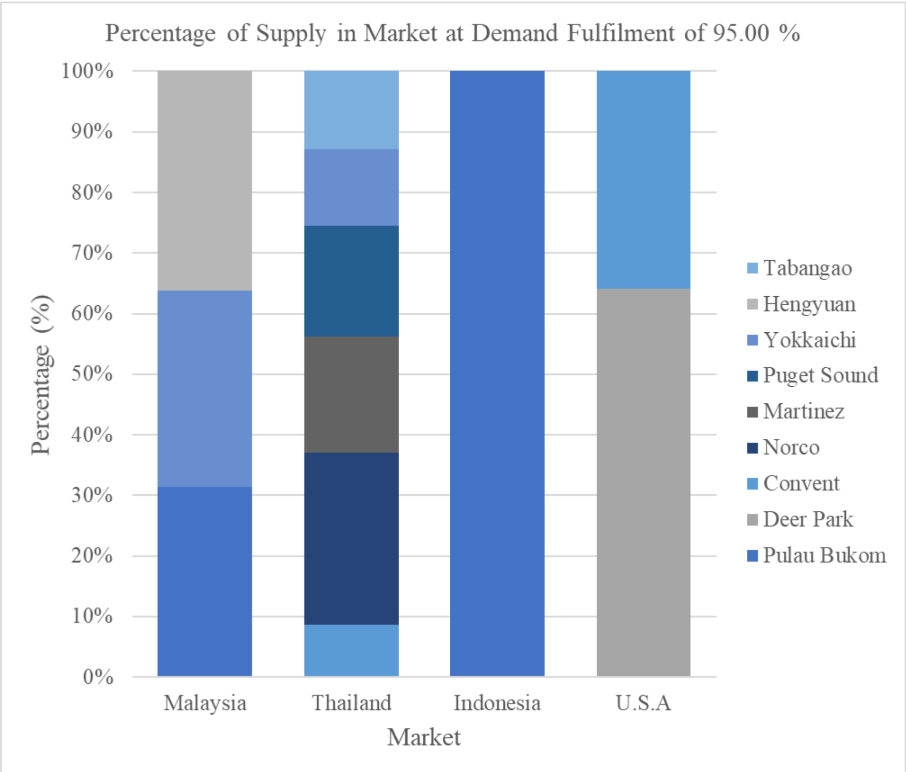

Figure 4.4: Percentage of Supply in Market at Demand Fulfilment of 95.00 %

As observed from Figure 4.1 to Figure 4.4, Shell Pulau Bukom supplied B20 to Indonesia regardless of demand fulfilments since Indonesia is close to Shell Pulau Bukom. Malaysia has B10 supplies mainly from Shell Pulau Bukom and Hengyuan Refining Company Berhad while Shell Yokkaichi also started to deliver B10 to Malaysia when demand fulfilment reached 80.00 %. The U.S.A. has B20 supplied mainly by Shell Deer Park. Shell Puget Sound and Shell Convent also supplies B20 to the U.S.A. when the B20 produced by Shell Deer Park alone cannot fulfil the demand required. Thailand which is having the largest demand and located in Asia acquires B20 from blending facilities located in Asia at demand fulfilment of 50.00 %. As demand fulfilment increases, the blending facilities in Asia are no longer able to satisfy the demand of B20 in Thailand. Hence, blending facilities in the U.S.A started to supply B20 to Thailand in order to accomplish the ever increasing B20 demand in Thailand.

The breakdown of biodiesels blended to supply markets' demand at different demand fulfilment are shown in Table 4.16. The data listed in Table 4.16 are illustrated as sunburst charts in Figure 4.5 to Figure 4.8. These charts display the diversity of biodiesel used at different demand fulfilment. The total sales, costs and revenue at each demand fulfilment including demand fulfilment of 50.00 % are listed in Table 4.17 and presented as a chart shown in Figure 4.9 for better illustration. The costs tabulated in Table 4.17 are then showed in Figure 4.10 for clearer view of each cost's percentage in the total cost.

Table 4.16: Biodiesel Breakdown in Total Biodiesel-Diesel Blends Produced at Different Demand Fulfilment

Demand Fulfilment (%)		**50.00**	**65.00**	**80.00**	**95.00**
Type of Biodiesel	**Resource Location**	**Percentage of Multi-Biodiesel in Total Biodiesel-Diesel Blends Produced (%)**			
Palm oil	Malaysia	10.20	18.56	19.36	20.34
	Thailand	0.00	0.00	0.00	1.52
Soybean	U.S.A.	36.36	40.33	41.33	34.81
Rapeseed	Canada	0.00	0.00	5.90	5.31
Coconut	Philippines	0.00	0.00	0.00	9.90
RCO	Malaysia	8.99	6.91	5.62	4.73
	Singapore	44.06	33.90	27.54	23.19
	Thailand	0.39	0.30	0.24	0.21

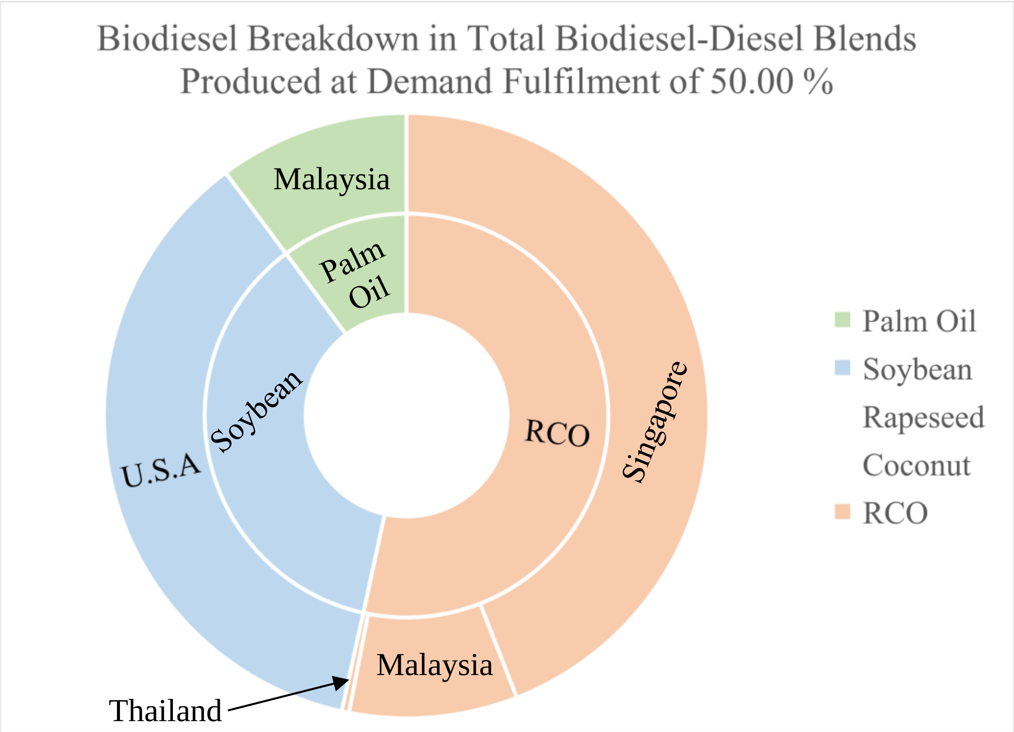

Figure 4.5: Biodiesel Breakdown in Total Biodiesel-Diesel Blends Produced at Demand Fulfilment of 50.00 %

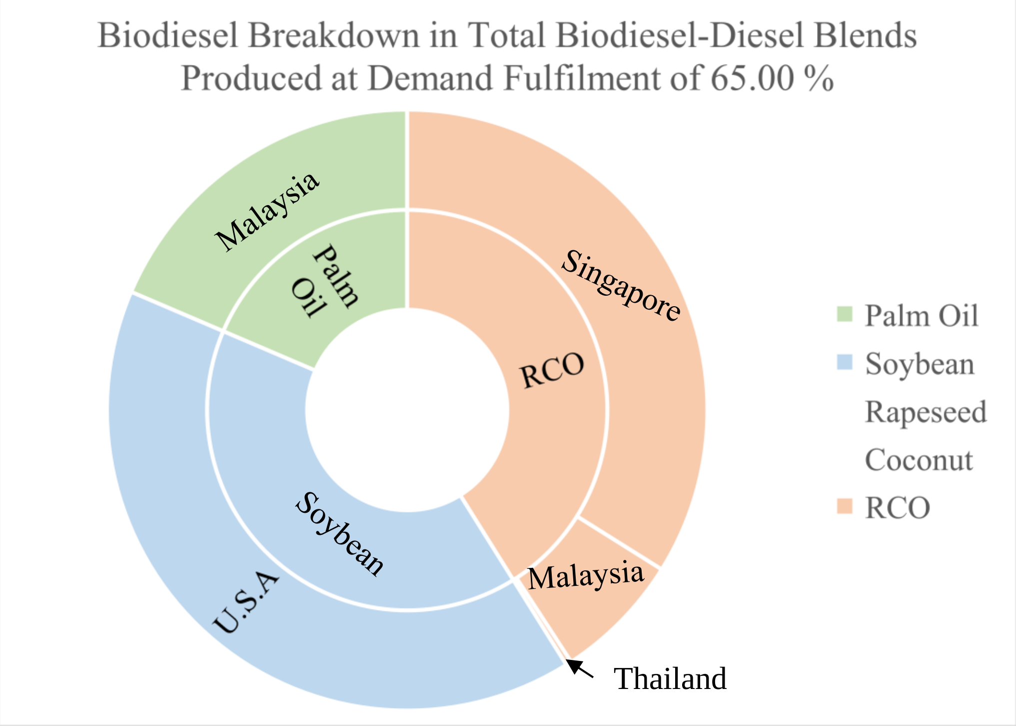

Figure 4.6: Biodiesel Breakdown in Total Biodiesel-Diesel Blends Produced at Demand Fulfilment of 65.00 %

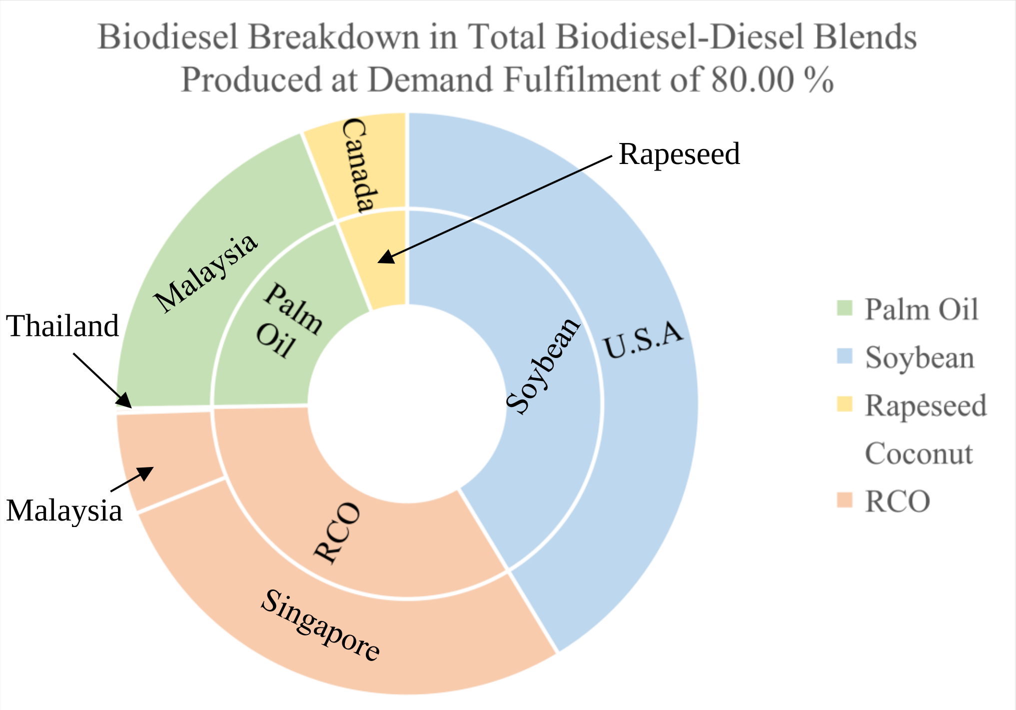

Figure 4.7: Biodiesel Breakdown in Total Biodiesel-Diesel Blends Produced at Demand Fulfilment of 80.00 %

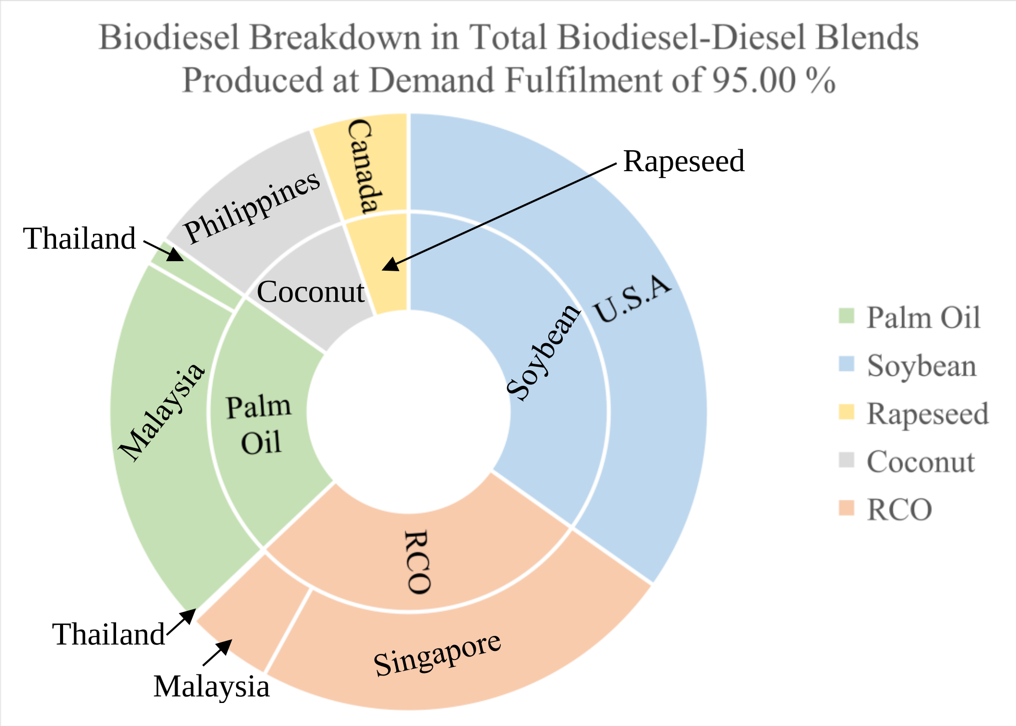

Figure 4.8: Biodiesel Breakdown in Total Biodiesel-Diesel Blends Produced at Demand Fulfilment of 95.00 %

Table 4.17: Tabulation of Sales, Costs and Revenues at Different Demand Fulfilments.

Demand Fulfilment (%)	**50.00**	**65.00**	**80.00**	**95.00**
Total Sales (RM 10 k/yr)	4223958.50	5491146.05	6758333.60	8025521.15
Total Feedstock Cost (RM 10 k/yr)	483562.37	658415.80	854155.85	1090718.39
Total Biodiesel Production Cost (RM 10 k/yr)	64098.83	87048.38	112955.05	142369.67
Total Biodiesel-Diesel Blend Production Cost (RM 10 k/yr)	647.47	841.04	1035.52	1230.00
Total Truck Transport Cost (RM 10 k/yr)	41603.77	63099.61	200342.59	264237.13
Total Water Transport Cost (RM 10 k/yr)	382811.79	974464.93	2128754.55	3690793.71
Revenue (RM 10 k/yr)	3251234.29	3707276.29	3461090.03	2836172.24

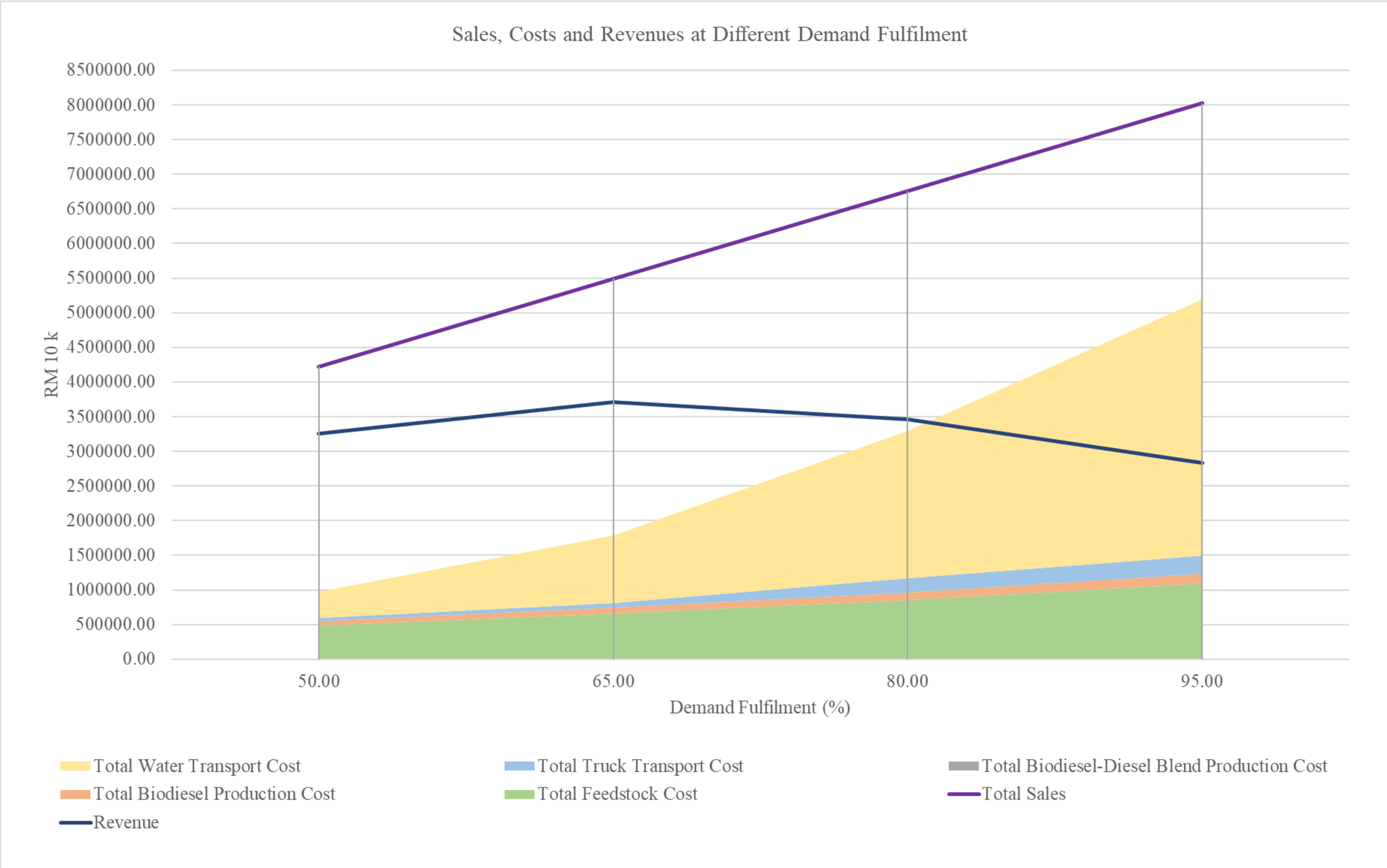

Figure 4.9: Sales, Costs and Revenues at Different Demand Fulfilment

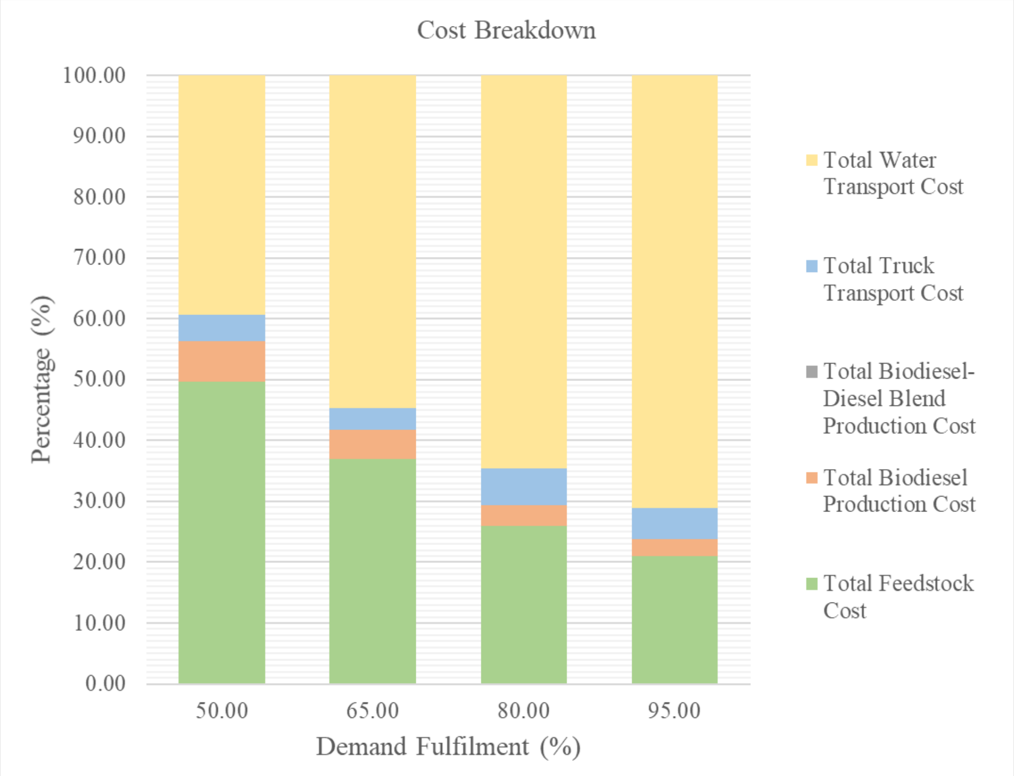

Figure 4.10: Cost Breakdown at Different Demand Fulfilment

From Figure 4.5 to Figure 4.8, the use of biodiesel in total biodiesel-diesel blends produced are more diverse as demand fulfilment increases. This is due to the limited capacities of biodiesel production plants set in this case study. Diversity of biodiesel used causes the costs, mainly the transportation costs to increase until one point where the revenue drops as the total sales gained mostly are used to pay the transportation costs as shown in Figure 4.9. As observed from Figure 4.10, the total feedstock cost for biodiesel production contributes around half of the total cost at demand fulfilment of 50.00 %. Nevertheless, the percentage of total feedstock cost for biodiesel production in total cost drops as demand fulfilment rises. The transport cost includes truck transport cost and water transport cost contributes more than 50.00 % of the total cost for demand fulfilments of 65.00 %, 80.00 % and 95.00 %. This is due to the more diverse biodiesel supplies and increase demand of biodiesel-diesel blends forces the supply chain to be more varied. As shown in Figure 4.9, supply chain at demand fulfilment of 65.00 % is the optimum as the revenue earned is the maximum while all the blends produced satisfied the biodiesel blends standard ASTM D7467 (for B6 to B20).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In conclusion, this project proposed an optimisation model to determine the multi-biodiesel utilisation in biodiesel-diesel blending with consideration of resources material balance, fuel property criteria and revenue. A demonstration case study was shown to evaluate the effects of market's demand fluctuation on supply chain's pattern and performance. The case studies are conducted at demand fulfilment of 50.00 %, 65.00 %, 80.00 % and 95.00 %. A 100.0 % demand fulfilment cannot be achieved as it is limited by the total amount of biodiesel obtainable from biodiesel producers set in the case.

As demand fulfilment increases, amount of biodiesel utilised increases. This causes the amount of biodiesel obtainable at cheaper price to be limited. The limitation of biodiesel available forces the utilisation of diverse biodiesel in biodiesel-diesel blends production. Utilisation of diverse biodiesel in biodiesel-diesel blends production causes shipping transportation costs to increase, contributing the most among the costs. Higher costs as the result of utilising multiple biodiesel mixtures in biodiesel-diesel blending resulting lower revenues. With the use of this supply chain optimisation model, suppliers are able to decide the supply chain that brings the most revenue while ensuring the sustainability of biodiesel supply chain. Diverse biodiesel utilisation strategic in biodiesel-diesel blend production at demand fulfilment of 65.00 % has the highest revenue amongst the cases at other demand fulfilment, which is RM 37072762.90 k/yr.

5.2 Recommendations for future work

Future improvement of this model can be broken down into few areas. Firstly, the complexity of model can be improved possibly by considering more biodiesel resource locations, production plants and blending facilities to make the model more complete. In addition, a more complete supply chain of biodiesel feedstock can be considered to improve the complexity of model. For example, includes biodiesel feedstock production from raw material in order to make the model more complex. Besides, sustainable aspect of the supply chain can be focused in future. Consideration of sustainability indexes of biodiesel feedstock in the model will help to provide insightful multi-biodiesel utilisation in biodiesel-diesel blending and supply chain system.

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APPENDICES

APPENDIX A: GAMS Coding for Proposed Model

```
Set
h "resource location"
/ ms_palm_oil, th_palm_oil, us_soybean, ca_rapeseed,
ph_coconut, ms_rco, sg_rco, th_rco /

i "biodiesel production plant"
/ palm_oil_m1, palm_oil_m2, palm_oil_m3, palm_oil_m4,
palm_oil_m5, palm_oil_m6, palm_oil_t1, palm_oil_t2, soybean_u1,
soybean_u2, soybean_u3, soybean_u4, rapeseed, coconut_p1,
coconut_p2, coconut_p3, coconut_p4, coconut_p5, rco_m, rco_s,
rco_t /

j "blending_facility"
/ pulau_bukom, deer_park, convent, norco, martinez,
puget_sound, yokkaichi, hengyuan, tabangao /

k "market"
/ malaysia, thailand, indonesia, usa / ;

Parameter
* Biodiesel Properties
db(i) "density of biodiesel at biodiesel production plant i in
kg/L"
       / palm_oil_m1     = 0.8591
         palm_oil_m2     = 0.8591
         palm_oil_m3     = 0.8591
         palm_oil_m4     = 0.8591
         palm_oil_m5     = 0.8591
         palm_oil_m6     = 0.8591
         palm_oil_t1     = 0.8591
         palm_oil_t2     = 0.8591
         soybean_u1      = 0.8850
         soybean_u2      = 0.8850
         soybean_u3      = 0.8850
         soybean_u4      = 0.8850
         rapeseed        = 0.8800
```

```
          coconut_p1      = 0.8605
          coconut_p2      = 0.8605
          coconut_p3      = 0.8605
          coconut_p4      = 0.8605
          coconut_p5      = 0.8605
          rco_m           = 0.8970
          rco_s           = 0.8970
          rco_t           = 0.8970        /

kvb(i) "ln (kinematic viscosity of biodiesel at biodiesel
production plant i)"
        / palm_oil_m1     = 1.545
          palm_oil_m2     = 1.545
          palm_oil_m3     = 1.545
          palm_oil_m4     = 1.545
          palm_oil_m5     = 1.545
          palm_oil_m6     = 1.545
          palm_oil_t1     = 1.545
          palm_oil_t2     = 1.545
          soybean_u1      = 1.411
          soybean_u2      = 1.411
          soybean_u3      = 1.411
          soybean_u4      = 1.411
          rapeseed        = 1.456
          coconut_p1      = 1.145
          coconut_p2      = 1.145
          coconut_p3      = 1.145
          coconut_p4      = 1.145
          coconut_p5      = 1.145
          rco_m           = 1.668
          rco_s           = 1.668
          rco_t           = 1.668         /

cnb(i) "cetane number of biodiesel at biodiesel production
plant i"
        / palm_oil_m1     = 52.00
          palm_oil_m2     = 52.00
          palm_oil_m3     = 52.00
          palm_oil_m4     = 52.00
          palm_oil_m5     = 52.00
          palm_oil_m6     = 52.00
```

```
         palm_oil_t1      = 52.00
         palm_oil_t2      = 52.00
         soybean_u1       = 50.90
         soybean_u2       = 50.90
         soybean_u3       = 50.90
         soybean_u4       = 50.90
         rapeseed         = 61.50
         coconut_p1       = 59.00
         coconut_p2       = 59.00
         coconut_p3       = 59.00
         coconut_p4       = 59.00
         coconut_p5       = 59.00
         rco_m            = 54.00
         rco_s            = 54.00
         rco_t            = 54.00          /

* Info on Biodiesel Production
* MT stands for metric tonne
bftc(h) "availability of feedstock at resource location h in
MT/yr"
       / ms_palm_oil      = 19800000
         th_palm_oil      = 3000000
         us_soybean       = 11020000
         ca_rapeseed      = 4225000
         ph_coconut       = 1615000
         ms_rco           = 222000
         sg_rco           = 1050000
         th_rco           = 10000          /

fc(h) "feedstock cost at resource location h in RM/MT"
       / ms_palm_oil      = 2357.00
         th_palm_oil      = 3819.29
         us_soybean       = 2694.00
         ca_rapeseed      = 3434.34
         ph_coconut       = 3604.67
         ms_rco           = 1077.45
         sg_rco           = 1749.80
         th_rco           = 1740.00        /
```

```
cx(i) "conversion of bio-oil to biodiesel at biodiesel
production plant i"
       / palm_oil_m1     = 93.60
         palm_oil_m2     = 93.60
         palm_oil_m3     = 93.60
         palm_oil_m4     = 93.60
         palm_oil_m5     = 93.60
         palm_oil_m6     = 93.60
         palm_oil_t1     = 93.60
         palm_oil_t2     = 93.60
         soybean_u1      = 98.30
         soybean_u2      = 98.30
         soybean_u3      = 98.30
         soybean_u4      = 98.30
         rapeseed        = 97.40
         coconut_p1      = 90.00
         coconut_p2      = 90.00
         coconut_p3      = 90.00
         coconut_p4      = 90.00
         coconut_p5      = 90.00
         rco_m           = 97.00
         rco_s           = 97.00
         rco_t           = 97.00         /

bstc(i) "availability of biodiesel at biodiesel production
plant i in MT/yr"
       / palm_oil_m1     = 300000
         palm_oil_m2     = 60000
         palm_oil_m3     = 180000
         palm_oil_m4     = 100000
         palm_oil_m5     = 100000
         palm_oil_m6     = 100000
         palm_oil_t1     = 291611
         palm_oil_t2     = 283503
         soybean_u1      = 301508
         soybean_u2      = 241206
         soybean_u3      = 335009
         soybean_u4      = 603016
         rapeseed        = 224456
         coconut_p1      = 72282
         coconut_p2      = 77445
```

```
         coconut_p3      = 68840
         coconut_p4      = 129075
         coconut_p5      = 61956
         rco_m           = 204000
         rco_s           = 1000000
         rco_t           = 8880          /

pdcb(i) "production cost of biodiesel at biodiesel production
plant i in RM/MT"
       / palm_oil_m1     = 321.41
         palm_oil_m2     = 321.41
         palm_oil_m3     = 321.41
         palm_oil_m4     = 321.41
         palm_oil_m5     = 321.41
         palm_oil_m6     = 321.41
         palm_oil_t1     = 520.81
         palm_oil_t2     = 520.81
         soybean_u1      = 367.36
         soybean_u2      = 367.36
         soybean_u3      = 367.36
         soybean_u4      = 367.36
         rapeseed        = 468.32
         coconut_p1      = 491.55
         coconut_p2      = 491.55
         coconut_p3      = 491.55
         coconut_p4      = 491.55
         coconut_p5      = 491.55
         rco_m           = 146.93
         rco_s           = 238.61
         rco_t           = 237.27        /
```

```
* Info on Blending Facilities
* ML stands for million liters
bd_cdc(j) "crude distillation capacity at blending facility j
in ML/yr"
       / pulau_bukom     = 24292
         deer_park       = 16369
         convent         = 12539
         norco           = 12015
         martinez        = 7555
         puget_sound     = 7188
         yokkaichi       = 12277
         hengyuan        = 8185
         tabangao        = 5037  /

coc(j) "crude oil cost at blending facility j RM/L"
       / pulau_bukom     = 0.88
         deer_park       = 0.88
         convent         = 0.88
         norco           = 0.88
         martinez        = 0.88
         puget_sound     = 0.88
         yokkaichi       = 0.87
         hengyuan        = 0.87
         tabangao        = 0.89  /
```

```
* Info on Demand
spb(k)   "selling price of biodiesel-diesel blend at market k
in RM/L"
       / malaysia         = 1.46
         thailand         = 2.27
         indonesia        = 2.71
         usa              = 3.25 /

b10dm(k) "B10 demand at market k in ML/yr"
       / malaysia         = 8852
         thailand         = 10950
         indonesia        = 0
         usa              = 0 /

b20dm(k) "B20 demand at market k in ML/yr"
       / malaysia         = 0
         thailand         = 0
         indonesia        = 6200
         usa              = 9199 /;
```

```
* Supply of feedstock to biodiesel production plant
* 1 indicates there is supply while 0 indicates no supply
Table supply(i,h) "supply of feedstock in biodiesel production plant i from resource location h"
            ms_palm_oil     th_palm_oil     us_soybean     ca_rapeseed     ph_coconut     ms_rco     sg_rco     th_rco
palm_oil_m1 1               0               0              0               0              0          0          0
palm_oil_m2 1               0               0              0               0              0          0          0
palm_oil_m3 1               0               0              0               0              0          0          0
palm_oil_m4 1               0               0              0               0              0          0          0
palm_oil_m5 1               0               0              0               0              0          0          0
palm_oil_m6 1               0               0              0               0              0          0          0
palm_oil_t1 0               1               0              0               0              0          0          0
palm_oil_t2 0               1               0              0               0              0          0          0
soybean_u1  0               0               1              0               0              0          0          0
soybean_u2  0               0               1              0               0              0          0          0
soybean_u3  0               0               1              0               0              0          0          0
soybean_u4  0               0               1              0               0              0          0          0
rapeseed    0               0               0              1               0              0          0          0
coconut_p1  0               0               0              0               1              0          0          0
coconut_p2  0               0               0              0               1              0          0          0
coconut_p3  0               0               0              0               1              0          0          0
coconut_p4  0               0               0              0               1              0          0          0
coconut_p5  0               0               0              0               1              0          0          0
```

```
rco_m       0           0           0           0           0           1       0       0
rco_s       0           0           0           0           0           0       1       0
rco_t       0           0           0           0           0           0       0       1
;

* Logistic
Table btd(i,j) "distance travelled by truck from biodiesel production plant i to blending facility j in km"
                         pulau_bukom     deer_park     convent     norco     martinez     puget_sound     yokkaichi
hengyuan     tabangao
         palm_oil_m1     6.00            19.77         23.96       67.89     44.88        13.33           15.40
304.00       11.40
         palm_oil_m2     13.30           27.07         31.26       75.19     52.18        20.63           22.70
323.00       18.70
         palm_oil_m3     4.00            17.77         21.96       65.89     42.88        11.33           13.40
302.00       9.40
         palm_oil_m4     4.10            17.87         22.06       65.99     42.98        11.43           13.50
307.00       9.50
         palm_oil_m5     3.20            16.97         21.16       65.09     42.08        10.53           12.60
307.00       8.60
         palm_oil_m6     12.50           26.27         30.46       74.39     51.38        19.83           21.90
324.00       17.90
```

palm_oil_t1	63.50	77.27	81.46	125.39	102.38	70.83	72.90	1729.00	68.90
palm_oil_t2	190.00	203.77	207.96	251.89	228.88	197.33	199.40	972.00	195.40
soybean_u1	28.07	11.10	469.93	516.60	3104.43	3851.16	37.47	27.17	33.47
soybean_u2	3.45	497.29	197.95	244.62	3382.84	4068.42	12.85	2.55	8.85
soybean_u3	41.27	3852.77	4184.29	4230.97	1213.45	300.95	50.67	40.37	46.67
soybean_u4	17.13	135.67	339.57	386.24	3233.17	3979.91	26.53	16.23	22.53
rapeseed	3.20	2417.00	2114.00	3303.98	4136.00	4172.00	12.60	2.30	8.60
coconut_p1	20.70	34.47	38.66	82.59	59.58	28.03	30.10	19.80	113.00
coconut_p2	13.00	26.77	30.96	74.89	51.88	20.33	22.40	12.10	112.00
coconut_p3	25.70	39.47	43.66	87.59	64.58	33.03	35.10	24.80	93.60
coconut_p4	4.10	17.87	22.06	65.99	42.98	11.43	13.50	3.20	1331.00

```
        coconut_p5      22.00           35.77          39.96        83.89     60.88        29.33           31.40
21.10         108.00
        rco_m           41.20           54.97          59.16        103.09    80.08        48.53           50.60
102.00        46.60
        rco_s           8.90            22.67          26.86        70.79     47.78        16.23           18.30
310.00        14.30
        rco_t           247.00          260.77         264.96       308.89    285.88       254.33          256.40
1811.00       252.40
;

Table bsd(i,j) "distance travelled by ship from biodiesel production plant i to blending facility j in km"
                        pulau_bukom     deer_park      convent      norco     martinez     puget_sound     yokkaichi
hengyuan      tabangao
        palm_oil_m1     28.19           16014.20       16181.51     16181.51  13577.39     12887.07        5035.11
0.00          2330.31
        palm_oil_m2     28.19           16014.20       16181.51     16181.51  13577.39     12887.07        5035.11
0.00          2330.31
        palm_oil_m3     28.19           16014.20       16181.51     16181.51  13577.39     12887.07        5035.11
0.00          2330.31
        palm_oil_m4     28.19           16014.20       16181.51     16181.51  13577.39     12887.07        5035.11
0.00          2330.31
```

palm_oil_m5	28.19	16014.20	16181.51	16181.51	13577.39	12887.07	5035.11	0.00	2330.31
palm_oil_m6	28.19	16014.20	16181.51	16181.51	13577.39	12887.07	5035.11	0.00	2330.31
palm_oil_t1	1353.60	14966.58	15061.73	15061.73	12789.68	11940.00	4334.16	0.00	2180.97
palm_oil_t2	1131.32	15367.70	15449.79	15449.79	13210.33	12356.57	4744.77	0.00	2475.83
soybean_u1	16042.36	0.00	0.00	0.00	0.00	0.00	11019.76	16012.71	13829.36
soybean_u2	16034.23	0.00	0.00	0.00	0.00	0.00	11076.43	15977.18	13901.72
soybean_u3	12927.25	0.00	0.00	0.00	0.00	0.00	7875.52	12928.87	10678.16
soybean_u4	16080.36	0.00	0.00	0.00	0.00	0.00	11070.36	16043.89	13884.64
rapeseed	15054.74	0.00	0.00	0.00	0.00	0.00	10563.86	14920.76	13327.17
coconut_p1	2401.15	13763.82	13997.69	13997.69	11226.41	10624.72	2756.10	2491.74	0.00
coconut_p2	2401.15	13763.82	13997.69	13997.69	11226.41	10624.72	2756.10	2491.74	0.00

```
        coconut_p3      2401.15         13763.82      13997.69    13997.69  11226.41      10624.72         2756.10
2491.74      0.00
        coconut_p4      2449.43         14015.12      14293.38    14293.38  11391.72      10917.57         3185.32
2613.64      0.00
        coconut_p5      2401.15         13763.82      13997.69    13997.69  11226.41      10624.72         2756.10
2491.74      0.00
        rco_m           330.44          15984.26      16118.78    16118.78  13631.99      12885.68         5082.04
0.00         2468.09
        rco_s           18.24           16049.41      16214.80    16214.80  13615.83      12923.34         5072.91
0.00         2369.74
        rco_t           1430.30         14910.40      15001.13    15001.13  12752.13      11893.35         4313.62
0.00         2209.27
;

Table bdtd(j,k) "distance travelled by truck from blending facility j to market k in km"
                         malaysia        thailand        indonesia       usa
        pulau_bukom      2.00            2.00            2.00            2.00
        deer_park        15.45           15.45           15.45           15.77
        convent          20.44           20.44           20.44           463.49
        norco            20.44           20.44           20.44           510.16
        martinez         40.88           40.88           40.88           638.91
        puget_sound      9.33            9.33            9.33            172.20
```

```
        yokkaichi       11.70           11.70           11.70           11.70
        hengyuan        100.00          1676.00         1.10            1.10
        tabangao        7.40            7.40            7.40            7.40
;

Table bdsd(j,k) "distance travelled by ship from blending facility j to market k in km"
                        malaysia        thailand        indonesia       usa
        pulau_bukom     330.45          1357.97         883.57          14151.67
        deer_park       15984.56        14961.39        16532.11        0.00
        convent         16119.30        15056.87        16771.45        0.00
        norco           16119.30        15056.87        16771.45        0.00
        martinez        13632.03        12784.18        13940.59        0.00
        puget_sound     12885.60        11934.44        13397.11        0.00
        yokkaichi       5082.10         4329.01         5527.48         9107.83
        hengyuan        0.00            0.00            1111.34         14197.33
        tabangao        2466.96         2178.40         2705.24         11816.37
;
```

```
Scalar
* Diesel Properties
DD       "density of diesel in kg/L" / 0.8400 /
KVD      "ln(kinematic viscosity of diesel)" / 1.179 /
CND      "cetane number of diesel" / 48.00 /

* Biodiesel-Diesel Production
Ref_C    "crude oil refining cost in RM/L" / 0.18 /
D_C      "diesel to crude oil ratio" / 0.2738 /
BB10R    "ratio of total biodiesel in B10" / 0.10 /
BB20R    "ratio of total biodiesel in B20" / 0.20 /

* Transportation Rate
Truck_C  "truck transportation rate in RM/MT.km" / 0.99 /
Water_C  "water transportation rate in RM/MT.km" / 0.27 /

* Fulfilment Percentage of Demand
FPD      "fulfilment percentage of demand" / 0.50 /;

Variables
* Decision Variables
x10(i,j)         "amount of various biodiesel in B10 at
blending facility j in ML/yr"
x20(i,j)         "amount of various biodiesel in B20 at
blending facility j in ML/yr"
m10(i,j)         "amount of various biodiesel in B10 at
blending facility j in MT/yr"
m20(i,j)         "amount of various biodiesel in B20 at
blending facility j in MT/yr"
y10(j)           "amount of diesel blended in B10 at blending
facility j in ML/yr"
y20(j)           "amount of diesel blended in B20 at blending
facility j in ML/yr"
w10(j,k)         "amount of B10 to demand k in ML/yr"
w20(j,k)         "amount of B10 to demand k in ML/yr"

* Material Balance Purpose
fr(i)            "amount of feedstock required in MT/yr"
tb10(j)          "total amount of biodiesel-diesel blend B10 at
blending facility j in ML/yr"
```

```
tb20(j)          "total amount of biodiesel-diesel blend B20 at
blending facility j in ML/yr"
tb_b10(j)        "total amount of biodiesel in B10 at blending
facility j in ML/yr"
tb_b20(j)        "total amount of biodiesel in B20 at blending
facility j in ML/yr"

* Density
d_b_b10(j)       "density of biodiesel mixture in B10 at
blending facility j in kg/L"
d_b_b20(j)       "density of biodiesel mixture in B20 at
blending facility j in kg/L"
d_b10(j)         "density of B10 at blending facility j in
kg/L"
d_b20(j)         "density of B20 at blending facility j in
kg/L"

* Natural Logarithm of Kinematic Viscosity
kv_b_b10(j)      "ln(kinematic viscosity of biodiesel mixture
in B10) at blending facility j"
kv_b_b20(j)      "ln(kinematic viscosity of biodiesel mixture
in B20) at blending facility j"
kv_b10(j)        "ln(kinematic viscosity of B10) at blending
facility j"
kv_b20(j)        "ln(kinematic viscosity of B20) at blending
facility j"

* Cetane Number
cn_b_b10(j)      "cetane number of biodiesel mixture in B10 at
blending facility j"
cn_b_b20(j)      "cetane number of biodiesel mixture in B20 at
blending facility j"
cn_b10(j)        "cetane number of B10 at blending facility j"
cn_b20(j)        "cetane number of B20 at blending facility j"
```

```
* For Objective Function
tfc              "total feedstock cost in RM 10k/yr"
tbpc             "total biodiesel production cost in RM 10k/yr"
trc              "total crude oil refining cost in RM 10k/yr"
tco              "total crude oil cost in RM 10k/yr"
tbdpc            "total biodiesel-diesel blend production cost
in RM 10k/yr"
tb(i,j)          "total amount of biodiesel sent from biodiesel
production plant i to blending facility j in MT/yr"
tbd(j,k)         "total amount of biodiesel-diesel blend from
blending facility j to market k in MT/yr"
ttc              "total truck transportation cost in RM 10k/yr"
twc              "total water transportation cost in RM 10k/yr"
ts               "total sales in RM 10k/yr"
z                "revenue in RM 10k/yr"
;

Positive Variables x10, x20, m10, m20, y10, y20, w10, w20, fr,
tb10, tb20, tb_b10, tb_b20, d_b_b10, d_b_b20, d_b10, d_b20,
kv_b_b10, kv_b_b20, kv_b10, kv_b20, cn_b_b10, cn_b_b20, cn_b10,
cn_b20, tfc, tbpc, trc, tco, tbdpc, tb, tbd, ttc, twc, ts;

tb10.lo(j) = 0.000001;
tb20.lo(j) = 0.000001;
tb10.l(j) = 1;
tb20.l(j) = 1;
tb_b10.l(j) = 1;
tb_b20.l(j) = 1;
d_b_b10.l(j) = 0.86;
d_b_b20.l(j) = 0.86;
d_b10.l(j) = 0.82;
d_b20.l(j) = 0.82;
```

```
Equations
         obj                      "revenue in RM 10k/yr"
         total_fc                 "total feedstock cost in
                                   RM 10k/yr"
         total_bpc                "total production cost of
                                   biodiesel in RM 10k/yr"
         total_rc                 "total crude oil refining cost
                                   in RM 10k/yr"
         total_co                 "total crude oil cost in
                                   RM 10k/yr"
         total_bdpc               "total production cost of
                                   biodiesel-diesel blend in
                                   RM 10k/yr"
         total_b(i,j)             "total amount of biodiesel
                                   sent from biodiesel i
                                   production plant to blending
                                   facility j in MT/yr"
         total_bd(j,k)            "total amount of biodiesel-
                                   diesel blend sent from
                                   blending facility j to market
                                   k in MT/yr"
         total_truck_trans_cost  "total truck transportation
                                   cost in RM 10k/yr"
         total_water_trans_cost  "total water transportation
                                   cost in RM 10k/yr"
         total_sales              "total sales in RM 10k/yr"

         b10_demand(k)            "demand of B10 in ML/yr"
         total_b10(j)             "total amount of biodiesel-
                                   diesel blend B10 at blending
                                   facility j in ML/yr"
         total_b_b10(j)           "total amount of biodiesel in
                                   B10 at blending facility j in
                                   ML/yr"
         total_b2_b10(j)          "total amount of biodiesel in
                                   B10 at blending facility j in
                                   ML/yr"
         mass_b_b10(i,j)          "mass of biodiesel i in B10 at
                                   blending facility j in MT/yr"
```

```
diesel_b10(j)           "amount of diesel used in B10
                        at blending facility j in
                        ML/yr"

b20_demand(k)           "demand of B20 in ML/yr"
total_b20(j)            "total amount of biodiesel-
                         diesel blend B20 at blending
                         facility j in ML/yr"
total_b_b20(j)          "total amount of biodiesel in
                         B20 at blending facility j in
                         ML/yr"
total_b2_b20(j)         "total amount of biodiesel in
                         B20 at blending facility j in
                         ML/yr"
mass_b_b20(i,j)         "mass of biodiesel at
                         biodiesel production plant i
                         in B20 at blending facility j
                         in MT/yr"
diesel_b20(j)           "amount of diesel used in B20
                         at blending facility j in
                         ML/yr"

total_b_uplimit(i)      "total biodiesel upper limit
                         in MT/yr"
total_fr_required(i)    "total feedstock required for
                         biodiesel at biodiesel
                         production plant i in MT/yr"
total_fr_uplimit(h)     "total feedstock uplimit from
                         resource location h in MT/yr"
total_d_uplimit(j)      "total diesel uplimit at
                         blending facility j in ML/yr"

density_b_b10(j)        "density of biodiesel mixture
                         in B10 at blending facility j
                         in kg/L"
density_b_b10_ll(j)     "lower limit of biodiesel
                         mixture density in B10 at
                         blending facility j in kg/L"
density_b_b10_ul(j)     "upper limit of biodiesel
                         mixture density in B10 at
                         blending facility j in kg/L"
```

```
density_b10(j)          "density of B10 at blending
                         facility j in kg/L"
density_b10_ll(j)       "lower limit of B10 density at
                         blending facility j in kg/L"
density_b10_ul(j)       "upper limit of B10 density at
                         blending facility j in kg/L"
density_b_b20(j)        "density of biodiesel mixture
                         in B20 at blending facility j
                         in kg/L"
density_b_b20_ll(j)     "lower limit of biodiesel
                         mixture density in B20 at
                         blending facility j in kg/L"
density_b_b20_ul(j)     "upper limit of biodiesel
                         mixture density in B20 at
                         blending facility j in kg/L"
density_b20(j)          "density of B20 at blending
                         facility j in kg/L"
density_b20_ll(j)       "lower limit of B20 density at
                         blending facility j in kg/L"
density_b20_ul(j)       "upper limit of B20 density at
                         blending facility j in kg/L"

lnkv_b_b10(j)           "ln(kinematic viscosity of
                         biodiesel mixture in B10) at
                         blending facility j"
lnkv_b_b10_ll(j)        "lower limit of ln(kinematic
                         viscosity of biodiesel
                         mixture in B10) at blending
                         facility j"
lnkv_b_b10_ul(j)        "upper limit of ln(kinematic
                         viscosity of biodiesel
                         mixture in B10) at blending
                         facility j"
lnkv_b10(j)             "ln(kinematic viscosity of
                         B10) at blending facility j"
lnkv_b10_ll(j)          "lower limit of ln(kinematic
                         viscosity of B10) at blending
                         facility j"
lnkv_b10_ul(j)          "upper limit of ln(kinematic
                         viscosity of B10) at blending
                         facility j"
```

```
lnkv_b_b20(j)             "ln(kinematic viscosity of
                           biodiesel mixture in B20) at
                           blending facility j"
lnkv_b_b20_ll(j)          "lower limit of ln(kinematic
                           viscosity of biodiesel
                           mixture in B20) at blending
                           facility j"
lnkv_b_b20_ul(j)          "upper limit of ln(kinematic
                           viscosity of biodiesel
                           mixture in B20) at blending
                           facility j"
lnkv_b20(j)               "ln(kinematic viscosity of
                           B20) at blending facility j"
lnkv_b20_ll(j)            "lower limit of ln(kinematic
                           viscosity of B20) at blending
                           facility j"
lnkv_b20_ul(j)            "upper limit of ln(kinematic
                           viscosity of B20) at blending
                           facility j"

CNo_b_b10(j)              "cetane number of biodiesel
                           mixture in B10 at blending
                           facility j"
CNo_b_b10_ll(j)           "lower limit for cetane number
                           of biodiesel mixture in B10
                           at blending facility j"
CNo_b10(j)                "cetane number of B10 at
                           blending facility j"
CNo_b10_ll(j)             "lower limit of cetane number
                           of B10 at blending facility
                           j"
CNo_b_b20(j)              "cetane number of biodiesel
                           mixture in B20 at blending
                           facility j"
CNo_b_b20_ll(j)           "lower limit for cetane number
                           of biodiesel mixture in B20
                           at blending facility j"
CNo_b20(j)                "cetane number of B20 at
                           blending facility j"
CNo_b20_ll(j)             "lower limit of cetane number
                           of B20 at blending facility
```

```
                                  j"
;

* Material Balance

* B10
b10_demand(k)..   sum(j,w10(j,k)) =e= FPD*b10dm(k);
total_b10(j)..   tb10(j) =e= sum(k,w10(j,k));
total_b_b10(j).. tb_b10(j) =e= BB10R*tb10(j);
total_b2_b10(j).. tb_b10(j) =e= sum(i,x10(i,j));
mass_b_b10(i,j).. m10(i,j) =e= 1000*x10(i,j)*db(i);
diesel_b10(j).. y10(j) =e= (1-BB10R)*tb10(j);

* B20
b20_demand(k)..   sum(j,w20(j,k)) =e= FPD*b20dm(k);
total_b20(j)..   tb20(j) =e= sum(k,w20(j,k));
total_b_b20(j).. tb_b20(j) =e= BB20R*tb20(j);
total_b2_b20(j).. tb_b20(j) =e= sum(i,x20(i,j));
mass_b_b20(i,j).. m20(i,j) =e= 1000*x20(i,j)*db(i);
diesel_b20(j).. y20(j) =e= (1-BB20R)*tb20(j);

total_b_uplimit(i).. sum(j,m10(i,j)+m20(i,j)) =l= bstc(i);
total_fr_required(i).. fr(i) =e=
(sum(j,m10(i,j)+m20(i,j)))*(100/cx(i));
total_fr_uplimit(h).. sum(i,fr(i)*supply(i,h)) =l= bftc(h);
total_d_uplimit(j).. y10(j)+y20(j) =l= D_C*bd_cdc(j);

* Density
density_b_b10(j).. d_b_b10(j) =e=
(1000*sum(i,m10(i,j)))/(tb_b10(j)*1000000);
density_b_b10_ll(j).. d_b_b10(j) =g= 0.82;
density_b_b10_ul(j).. d_b_b10(j) =l= 0.90;

density_b10(j).. d_b10(j) =e=
((1000*sum(i,m10(i,j)))+(y10(j)*DD*1000000))/(tb10(j)*1000000);
density_b10_ll(j).. d_b10(j) =g= 0.81;
density_b10_ul(j).. d_b10(j) =l= 0.87;
```

```
density_b_b20(j).. d_b_b20(j) =e=
(1000*sum(i,m20(i,j)))/(tb_b20(j)*1000000);
density_b_b20_ll(j).. d_b_b20(j) =g= 0.82;
density_b_b20_ul(j).. d_b_b20(j) =l= 0.90;

density_b20(j).. d_b20(j) =e=
((1000*sum(i,m20(i,j)))+(y20(j)*DD*1000000))/(tb20(j)*1000000);
density_b20_ll(j).. d_b20(j) =g= 0.81;
density_b20_ul(j).. d_b20(j) =l= 0.87;

* ln(Kinematic Viscosity)
lnkv_b_b10(j).. kv_b_b10(j) =e=
sum(i,(m10(i,j)/(tb_b10(j)*d_b_b10(j)*1000))*kvb(i));
lnkv_b_b10_ll(j).. kv_b_b10(j) =g= 0.6419;
lnkv_b_b10_ul(j).. kv_b_b10(j) =l= 1.792;

lnkv_b10(j).. kv_b10(j) =e=
sum(i,((m10(i,j)/(tb10(j)*d_b10(j)*1000))*kvb(i)))+(((y10(j)*DD
*1000)/(tb10(j)*d_b10(j)*1000))*KVD);
lnkv_b10_ll(j).. kv_b10(j) =g= 0.6419;
lnkv_b10_ul(j).. kv_b10(j) =l= 1.411;

lnkv_b_b20(j).. kv_b_b20(j) =e=
sum(i,(m20(i,j)/(tb_b20(j)*d_b_b20(j)*1000))*kvb(i));
lnkv_b_b20_ll(j).. kv_b_b20(j) =g= 0.6419;
lnkv_b_b20_ul(j).. kv_b_b20(j) =l= 1.792;

lnkv_b20(j).. kv_b20(j) =e=
sum(i,((m20(i,j)/(tb20(j)*d_b20(j)*1000))*kvb(i)))+(((y20(j)*DD
*1000)/(tb20(j)*d_b20(j)*1000))*KVD);
lnkv_b20_ll(j).. kv_b20(j) =g= 0.6419;
lnkv_b20_ul(j).. kv_b20(j) =l= 1.411;

* Cetane Number
CNo_b_b10(j).. cn_b_b10(j) =e= -
23.48+(61.6828*exp(kv_b_b10(j)))-
(12.7738*(exp(kv_b_b10(j)))*(exp(kv_b_b10(j))))+(0.87697*(exp(k
v_b_b10(j)))*(exp(kv_b_b10(j)))*(exp(kv_b_b10(j))));
CNo_b_b10_ll(j).. cn_b_b10(j) =g= 47.00;
```

```
CNo_b10(j).. cn_b10(j) =e= -23.48+(61.6828*exp(kv_b10(j)))-
(12.7738*(exp(kv_b10(j)))*(exp(kv_b10(j))))+(0.87697*(exp(kv_b1
0(j)))*(exp(kv_b10(j)))*(exp(kv_b10(j))));
CNo_b10_ll(j).. cn_b10(j) =g= 40.00;

CNo_b_b20(j).. cn_b_b20(j) =e= -
23.48+(61.6828*exp(kv_b_b20(j)))-
(12.7738*(exp(kv_b_b20(j)))*(exp(kv_b_b20(j))))+(0.87697*(exp(k
v_b_b20(j)))*(exp(kv_b_b20(j)))*(exp(kv_b_b20(j))));
CNo_b_b20_ll(j).. cn_b_b20(j) =g= 47.00;

CNo_b20(j).. cn_b20(j) =e= -23.48+(61.6828*exp(kv_b20(j)))-
(12.7738*(exp(kv_b20(j)))*(exp(kv_b20(j))))+(0.87697*(exp(kv_b2
0(j)))*(exp(kv_b20(j)))*(exp(kv_b20(j))));
CNo_b20_ll(j).. cn_b20(j) =g= 40.00;

* Costs
total_fc.. tfc =e= (sum(h,
sum(i,fr(i)*supply(i,h))*fc(h)))/10000;
total_bpc.. tbpc =e= (sum(i,sum(j,
m10(i,j)+m20(i,j))*pdcb(i)))/10000;
total_rc.. trc =e=
(sum(j,((y10(j)+y20(j))/D_C)*1000000)*Ref_C)/10000;
total_co.. tco =e=
(sum(j,coc(j)*(((y10(j)+y20(j))/D_C)*1000000)))/10000;
total_bdpc.. tbdpc =e= (trc+tco)/(0.90*10000);
total_b(i,j).. tb(i,j) =e= m10(i,j)+m20(i,j);
total_bd(j,k).. tbd(j,k) =e=
(w10(j,k)*d_b10(j)*1000)+(w20(j,k)*d_b20(j)*1000);
total_truck_trans_cost.. ttc =e=
Truck_C*(sum(j,sum(i,tb(i,j)*btd(i,j)))+sum(k,sum(j,tbd(j,k)*bd
td(j,k))))/10000;
total_water_trans_cost.. twc =e=
Water_C*(sum(j,sum(i,tb(i,j)*bsd(i,j)))+sum(k,sum(j,tbd(j,k)*bd
sd(j,k))))/10000;

* Sales
total_sales.. ts =e=
(sum(k,sum(j,(w10(j,k)+w20(j,k))*1000000*spb(k))))/10000;
```

```
* Objective Function
obj.. z =e= ts-tfc-tbpc-tbdpc-ttc-twc;

Model FYP /all/ ;

Solve FYP using nlp maximizing z ;

Display x10.l, m10.l, y10.l, w10.l, d_b10.l, kv_b10.l,
cn_b10.l, x20.l, m20.l, y20.l, w20.l, d_b20.l, kv_b20.l,
cn_b20.l, tfc.l, tbpc.l, tbdpc.l, tb.l, tbd.l, ttc.l, twc.l,
ts.l, z.l;
```