Modeling and Optimization of Biomass Supply Chain for Energy, Chemicals and Materials Productions

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

In the growing concerns towards global environmental qualities and sustainable feedstocks supplies, scientific and technological efforts were intensified to utilize alternative renewable resources. In this regard, biomass appeared to be one of the potential feedstocks because it is generally carbon neutral and essentially renewable. Furthermore, biomass is virtually found in every part of the world in abundance and could provide socio-economic benefits. However, if it is not managed properly, biomass will be less competitive due to several issues that are associated with its supply chain. Typical biomass supply chain has a series of activities such as growing, harvesting, transporting, aggregating, and conversion which systematic and efficient flows of materials from the fields to the users are highly important. Biomass has competing uses, different kinds and origins which are potentially exploitable, poor geographic distributions for retrieving and transporting, and variations in physical and chemical properties. It is difficult to make informed decision for any biomass utilization project without having an optimal supply chain.

This research intended to solve those issues by modeling and optimizing biomass supply chains for manufacturing energy, chemicals, and materials based on their respective processing routes. The aim was not only to focus on energy production from biomass but also to include chemicals and materials because of several factors such as an emerging cost competitive energy resource such as shale gas, highly volatile energy prices, and customer's preparedness and acceptances. Furthermore, it also could leverage biomass plantations on the producers' sides. The biomass supply chain model has considered annual profitability of producing products as the performance indicator. It was derived from revenues of selling the products subtracted all the associated costs such as biomass cost, transportation cost, production cost, and emission treatment costs from transportation and production activities. It summed up simultaneously all the profitable processing options that have existed in the superstructure to yield the optimal value, while a single ownership was assumed for the whole supply chain's facilities.

Three optimization models have been developed and implemented in GAMS (General Algebraic Modeling System). The first one was the supply chain's optimization for Omtec Inc., located in Southwestern Ontario. It was a research collaboration between Omtec and the Department of Chemical Engineering, University of Waterloo, under the Natural Sciences and Engineering Research Council of Canada's Engage funding. Currently, this company produces bio-filler and briquette from wheat straw. They were planning for business expansion and to diversify the existing products' portfolios for future

investment. It involved utilizations of biomass sources other than wheat straw and productions of products other than bio-filler and briquette. A superstructure that has assisted in the model's formulation provided alternatives in the biomass processing routes which in turn aimed for profit maximization. Optimal results indicated that an annual profit of $ 22,618,673 was expected to be achieved, and this value was contributed mainly by the sales of bio-filler, bio-ethanol and by-products from the milling plant. The developed model has offered flexibilities in biomass resources utilization and technological uses for Omtec Inc. Since the model only considered biomass cost, transportation cost and production cost, it did not evaluate environmental performance in the supply chain.

The second optimization model was for the supply chain of Malaysian palm oil empty fruit bunches for multi-products productions. As one of the main palm oil producer in the world, Malaysia within its biomass initiatives and strategic plans has promoted the local biomass source utilizations for value-added products. The developed model has considered environmental performance in the supply chain by introducing emissions from transportation and production activities as one of decision variables. The superstructure showed processing alternatives for converting the biomass source into intermediates and products, transportation networks between processing facilities, and options for product's direct sale or for further refinements. Particularly, option for directly selling the produced product versus further refinement was relevant due to the economic uncertainties. With the available parameters, the optimal profit was found to be $ 713,642,269 per year. This economic bonanza was seemed ideal and have lack of optimal selections for processing routes and transportation modes.

The third and the last model has extended the second model by incorporating integer variables for important decisions related to the best processing routes and transportation modes in the supply chain. With numerous alternatives available, selecting best processing route for producing a product was imperative because of several factors associated with that such as product's competitiveness, viability and status of technology, environmental impacts, and so on. The optimal decisions about transportation amounts and modes have directly influenced the overall economic profitability as well as biomass accessibility and mobility. At a planning stage, questions might arise whether to use truck, train, barge or pipeline for transporting biomass and derived products from processing facilities to the desired destinations in the most economical way. With that in mind, the model has considered all of these dilemmas and provided useful information. The previous superstructure has been modified to include states of produced products whether they were solid, liquid or gases. Assignments for the transportation modes were done according to this modification. With the given parameters and constraints, the optimal annual profit was $1,561,106,613 per year.

Since majority of utilization projects involving biomass are still under research and development stages and there are difficulties to consolidate real data, approximations of models' parameters could not be avoided. The obtained optimal values were subjected to the qualities and availabilities of these approximated parameters. However, sensitivity analysis were performed by varying selected parameters and the effects to the objective functions were recorded. All in all, it was a strong hope that this research could solve typical issues related to the biomass supply chain and would integrate well with the efforts to simulate the biomass utilization process individually.

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I would like to express sincere gratitude to Department of Chemical Engineering, University of Waterloo for letting me fulfill my dream of being a student here. My deep acknowledgments are certainly dedicated to my supervisors, Professor Ali Elkamel and Professor Leonardo Simon for their endless helps and motivations throughout this enriching journey. They have taught me lot of things apart from research works and typical supervisions such as determinations, dedications, and commitments. These acknowledgements are also for my external examiner, Professor Helen Shang of Laurentian University, and for my research committee members; Associate Professor Ting Tsui, Associate Professor Aiping Yu, and Associate Professor Fatma Gzara.

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Dedications

In the name of Allah, the Most Beneficent and the Most Merciful for blessing me with the ability to seek knowledge and ability to feel wisdom. This PhD journey came to the end. It was a collection of stories that blended joys and struggles, smiles and cries, energetic and fatigue. Alhamdulillah, thank you to the God.

I dedicate this thesis to my lovely wife, Siti Noredyani Abdul Rahman for her endless supports, sacrifices and prayers, and to my adorable kids, Nur Iman Amani, Iman Aqeef and Nur Iman Amelia. This dedication also for my parents, Abdul Razik Sulaiman, Rosnah Udin, Abdul Rahman Jusoh and Shamsiah Mamat for their non-stop beliefs, motivations and prayers. To all my family members in Jerantut; Rozamzila Abdul Razik, Nor Hazana Abdul Razik, Noor Azian Abdul Razik, and Nor Nadiera Fazlin Abdul Razik, and in Kota Bharu; Muhammad Hafidz Abdul Rahman, Borhan Sidqy Abdul Rahman, Arifah Syahirah Abdul Rahman and Faris Marwan Abdul Rahman, and to all my friends in Canada and Malaysia, thank you very much!

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Abbreviations

ASTM	American Society for Testing and Material
BARON	Branch-And-Reduce Optimization Navigator
BSC	Biomass Supply Chain
CMC	Carboxymethyl Cellulose
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DLF	Dry Long Fiber
EFB	Empty Fruit Bunch
HEC	Hydroxyethyl Cellulose
HP	High Pressure
LP	Linear Programming
LP	Low Pressure
MF	Melamine Formaldehyde
MIP	Mixed Integer Programming
MOILP	Multi-Objective Integer Linear Programming
MP	Medium Pressure
MSW	Municipal Solid Waste
NCC	Nanocrystalline Cellulose
NFC	Nanofibrillated Cellulose
NLP	Non-linear Programming
PE	Polyethylene
PF	Phenol Formaldehyde
PHA	Polyhdroxyalkanoates
PLA	Polyactide
POM	Polyoxymethylenes
SM	Simulation Model
SP	Stochastic Programming
TPS	Thermoplastic Starch
UF	Urea Formaldehyde
VMI	Vendor-managed Inventory

Chapter 1

Introduction

In this chapter, overviews about biomass and the potentials and benefits of utilizing biomass for energy, chemicals, and materials production are explained to provide background motivations for this research. Positive attributes possessed by biomass resources are briefly discussed in the context of sustainability.

1.1 Biomass Definition and Classification

Biomass can be defined as biological or organic material that is derived from living or recently living organisms (www.biomassenergycentre.org.uk). These organisms relate to the five kingdoms in biology which are plants, animals, fungi, protists and monerans. While plants, animals and fungi are well known, protists are referred to any one-celled organisms including protozoans, eukaryotic algae and slime molds, while monerans include bacteria, blue-green algae, and various primitive pathogens. According to Wereko-Brobby & Hagen (1996), biomass is found in virtually every part of the world and it is not only forms an essential core component of the earth's life sustaining system, but it also has been consumed extensively and continually for human civilization and development. In addition, biomass is a highly diverse and complex resource which requires study in a wholly holistic context, with a full recognition of the interdependencies in the overall ecological system such as people, land, water, nutrients and all the five kingdoms of life.

Even though there are different types of biomass classifications, generally it can be divided into four general classes according to its sources. These four classes include biomass from trees, dedicated crops, agricultures, and wastes or residues (Wereko-Brobby & Hagen, 1996). Biomass from trees, also known as woody biomass, is by far the most commonly used and can be divided into virgin wood and forestry residuals. Dedicated crops or purposely grown crops are planted with specific purposes such as miscanthus, switchgrass, forage sorghum, poplar, and hybrid willow. The most significant division of biomass from agricultures is between those that are predominantly dry such as straw, stalk, bunch, stover, and rusk, and those that are wet such as animal dung and poultry manure. For instance, wheat straw and palm oil empty fruit bunch (EFB) are among typical examples of dry agricultural biomass. Biomass from plants whether they are from trees, energy crops or agricultures are often referred to as ligno-cellulosic biomass. Biomass from wastes and residues meanwhile include municipal solid wastes (MSW), which is defined as wastes of durable goods, non-durable goods, containers and packaging, food scraps, yard trimmings, and miscellaneous inorganic wastes from residential, commercial, and industrial sources (Demirbas, 2004).

1.2 Renewable Resources for Energy, Chemicals and Materials Productions

Biomass is essentially renewable which is mainly composed of carbon, hydrogen and oxygen, and regarded to be sustainable raw materials that compete directly with fossil fuel resources because they are both sharing similar conversion processes. Basically, renewable refers to the capability of a substance to be restored when the initial stock has been exhausted. However, there are more scientific ways to define renewability of a substance. For example, Wereko-Brobby and Hagen (1996) have introduced a renewability ratio concept as the ratio of replenishment rate to depletion rate. Even though both rates were unusually known, it is obvious that the renewability ratio value for renewable substance be always greater than one. Zhang and Long (2010) have talked about percent renewable (PR), where for instance, biodiesel possesses 30% of PR value while fossil fuels have 0% of PR value. Another definition given by American Society for Testing and Material (ASTM) D6866, which refers to the content of carbon 14 or radiocarbon, a weakly radioactive isotope that naturally occurring element in all living things (www.astm.com). As a general comparison, contemporary biomass has 100% of radiocarbon while fossil fuels have 0% of radiocarbon. This renewability of biomass is significantly important criteria to substitute the depleted fossil resources for sustainable energy, chemicals, and materials productions. In addition, biomass feedstocks are geographically dispersed worldwide as to provide equivalence of resources sharing, to ensure a balanced socioeconomic development between urban and rural, and it also can sustain essentially the earth's ecological system through a balance carbon cycle.

The potentials of biomass in substituting fossil fuels for energy production have constantly attracted growing interests from industries, academia and policy makers. The main reasons behind this condition are due to environmental effects associated with the burning of fossil fuels and global energy security threats. For environmental effects, one of common greenhouse gas that released from fossil fuel combustion is carbon dioxide. As the same effect in a greenhouse, this gas traps the heat and makes the world warmer. Carbon dioxide emission data from fossil fuels burning is shown in Figure 1.1.

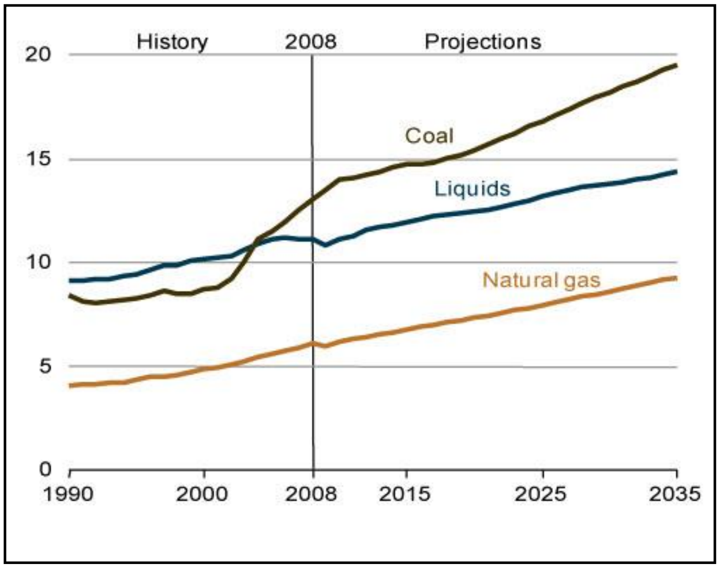

Figure 1.1 World energy-related carbon dioxide emissions by fuel type in billion metric tons, 1990-2035 (www.iea.org)

As the worldwide population increases and third world nations develop, energy demand continues to grow (Evans et al., 2010). Table 1.1 shows the world primary energy demand that is projected until 2035. As clearly can be seen, as the total worldwide demands for energy keep increasing year-by-year, biomass and other renewables are expected to gain significant contributions in meeting these demands. By 2050, estimation was made that biomass could provide nearly 38% of the world's direct fuel use and 17% of the world's electricity (Demirbas, 2004).

Table 1.1 World primary energy demands in metric tonne of oil equivalent (adopted from www.eia.org)

Primary energy	1980	2008	2015	2020	2030	2035
Coal	1792	3315	3892	3966	3984	3934
Oil	3107	4059	4252	4346	4550	4662
Gas	1234	2596	2919	3132	3550	3748
Nuclear	186	712	818	968	1178	1273
Hydro	148	276	331	376	450	476
Biomass	749	1225	1385	1501	1780	1957

Other renewables	12	89	178	268	521	699
Total	7229	12271	13776	14556	16014	16748

In the case of chemicals productions from biomass, similar attribute of sustainable feedstocks supply associated with biomass has gained remarkable interests especially in European Countries. A country like The Netherlands has a specific target for substituting petrochemical-based bulk chemicals with bio-based bulk chemicals. In Port of Rotterdam, one of the busiest ports in the world, short-term (0-10 year) target has been set-up for substituting 10-15% of fossil oil-based bulk chemicals by bio-based bulk chemicals, especially for oxygenated bulk chemicals such as ethylene glycol and propylene glycol, iso-propanol and acetone, butylene and methylketone, and also for the replacement of methyl tertiary butyl ether by ethyl tertiary butyl ether (Blaauw et al., 2008). While for the mid-term target (10-20 years) there is clear potential for a bio-based production of ethylene, acrylic acid and N-containing bulk chemicals such as acrylonitrile, and acrylamide. Bio-based building blocks, specifically carbohydrate-based building blocks could be used for the production of new generation bio-based bulk chemicals and polymers with a unique structure. However, the authors stated that a much larger impact might be expected for the production of bulk chemicals from bio-based resources (biomass) if the structures are identical to today's bulk chemicals.

Materials productions from biomass can be realized either from the derivation of bio-based bulk chemicals or as by-products from biomass conversion processes. In the case of bio-char or charcoal, it is produced from thermal conversion of biomass via pyrolysis. Bio-char is used as soil enhancer which will increase food security and cropland diversity in areas with severely depleted soils, scarce organic resources, and inadequate water and chemical fertilizer supplies (Erick et al., 2001).

1.3 Research Objectives

Having discussed the importance and benefits of utilizing biomass as an alternative feedstock, this research will focus about the modeling and optimization of biomass supply chain for energy, chemicals and materials productions. Specifically, the research objectives are highlighted in the followings:

- Construct superstructures that show important stages in a Biomass Supply Chain (BSC) that include biomass collection, pre-processing, storage and transportation, main processing and further processing to produce sustainable energy, chemicals and materials.

- Formulate mathematical models to optimize the supply chains with annual profitability as the objective function. It will search for optimal results that should include yields per year, selection of technologies and processing routes, selection of transportation modes, emission levels and so on. The developed models should evolve from the basic linear programming (LP) to a more complex one that might include mixed integer programming (MIP) and non-linear programming (NLP).
- Implement all the formulations in General Algebraic Modeling System (GAMS) and obtain the optimal results as well as carry out relevant analysis of the results.

1.4 Organization of the Thesis

The thesis is organized in six chapters as follows:

Chapter 1: Introduction

This chapter discusses the overviews of biomass and biomass utilizations as a renewable feedstock. It also discusses about the sustainability potentials of energy, chemicals and materials productions from biomass.

Chapter 2: Background and Process Description

This chapter provides background knowledge on the biomass supply chain and its components. Brief descriptions about biomass processes and previous works in the biomass supply chain's optimization models are summarized as to find the knowledge's gap.

Chapter 3: Modeling and Optimization of Biomass to Bio-products Supply Chain: A Research Collaboration with Omtec Incorporated

This chapter presents a paper-based results about the basic LP supply chain model that has been proposed to Omtec Inc. for their business expansion plan. Different biomass sources, multiple technologies and ranges of products are incorporated in the model.

Chapter 4: Multi-products Productions from Malaysian Oil Palm Empty Fruit Bunch (EFB): Analyzing Economic Potentials from Optimal Supply Chain

This chapter presents paper-based results about the optimal supply chain model of multi-products productions from Malaysian EFB. The model is formulated using LP. It takes a case study of the three states in Peninsula Malaysia that provide EFB sources. The transportation networks between processing facilities in the superstructure and emission considerations are emphasized.

Chapter 5: Multi-products Productions from Malaysian Oil Palm Empty Fruit Bunch (EFB): Selection for Optimal Process and Transportation Mode

This chapter presents paper-based results and extends the optimal supply chain model of multi-products productions from Malaysian EFB that is discussed in Chapter 4. The model incorporates integer variables as to select the best processing routes and transportation modes.

Chapter 6: Conclusions and Future Work

This chapter gives the overall concluding remarks gained from this research and suggests recommendations for future works.

Chapter 2

Background and Process Description

In this chapter, literatures were reviewed to provide background knowledge related to the biomass supply chain components and the way to optimize the inter-relating components. Brief descriptions about biomass processes were provided and previous works of supply chain optimization models were summarized. From the summary, this research has identified its novelty and expected contributions.

2.1 Supply Chain, Supply Chain Design and Supply Chain Management

In defining the supply chain and understanding the Supply Chain Management (SCM), La Londe and Masters (1994) have proposed the supply chain as set of firms that pass materials forward, which in practice it may involve scores or hundreds of firms for technologically complex products. The authors have also referred to the strategy of applying integrated logistics management to the all elements in a supply chain as SCM. Lambert et al. (1998) have used different name of supply SCM as logistics management which involve managing of goods or materials from point of origin to point of consumption, and in some cases even to the point of disposal. Simchi-Levi et al. (2000) have defined SCM as set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses and stores, so that merchandise is produced and distributed at the right quantities, to the right locations and at the right time, in order to minimize system-wide costs while satisfying service level requirements. Mentzer (2001) has defined a supply chain as a set of three or more companies directly linked by one or more of the upstream and downstream flows of products, services, finances, and information from a source to a customer, while SCM involves with management efforts by the organizations in the supply chain.

Manufacturing of energy, chemicals and materials from biomass are no different with other manufacturing industries in terms of requiring efficient SCM. As majority of the involved technologies are emerging and the products are relatively new to the market, productions should ensure their economic viabilities and carry positive reputations to the environment. This is where SCM would be playing significant roles especially when dealing with biomass systems. Typical issues related to the biomass systems are summarized in the followings;

- Lack of experiences with time-sensitive collections, handlings, storages, transportations and delivery operations to ensure year-round supplies of large of biomass feedstocks (Zhang et al., 2012).

- Biomass sources are known to have high physical and chemical properties variabilities (PPD Inc. 2011). These facts might be due to several reasons such as biomass type, location, soil condition, harvesting season, handling and pre-treatment used.
- Poor geographic distribution of biomass sources for retrieving and transporting, as well as their high content in ash and potentially corrosive components in some varieties (Perpina et al., 2008).
- Multiple uses of biomass sources such as for energy, food, feed, building and construction materials, fertilizers and so on, which will almost certainly are competing on each other (Wereko-Brobby C.Y. and Hagen E.B., 1996). In addition, it is always more than one of biomass sources could be used for the same utilization purpose depending to the availability, price, and quality.

Based on the above-mentioned issues, this research has focused on the design of Biomass Supply Chain (BSC) for energy, chemicals and materials productions. The design of the supply chain is one of the important elements in SCM. The block diagrams in Figure 2.1 represent the components in typical BSC. In the following sub-sections, the descriptions for each supply chain component are provided.

2.2 Biomass Production and Collection

Utilizations of biomass was expected to show gradual substitutions of fossil resources in the near future. In order to achieve this expectation, first and foremost, biomass resources need to be produced and collected in a sustainable manner. Beside agricultural residues, one type of biomass feedstocks that offers many advantages as a third generation feedstock is dedicated or purposely-grown crops. Dedicated crops are ligno-cellulosic raw materials which being cultivated that may provide sustainable biomass resources in the productions of bio-energy, bio-chemicals, bio-materials as well as other bio-products. In the view of agricultural diversification as suggested by Oo et al. (2012), dedicated crops offer farmers attractive option for number of important reasons such as high yield, low crop maintenance, growing favorable incentives and policies from decision makers, soil quality restoration and other environmental benefits. In general, dedicated crops can be divided into two types; i) woody, such as willow and poplar; ii) herbaceous, such as miscanthus, switchgrass, sorghum, Indian grass, native tall grasses, reed canary grass, big blue stem, etc. For farmers that have experiences dealing with conventional herbaceous crops such as hay, herbaceous dedicated crops are more preferable to cultivate over woody dedicated crops because the farmers may use the existing agricultural equipment.

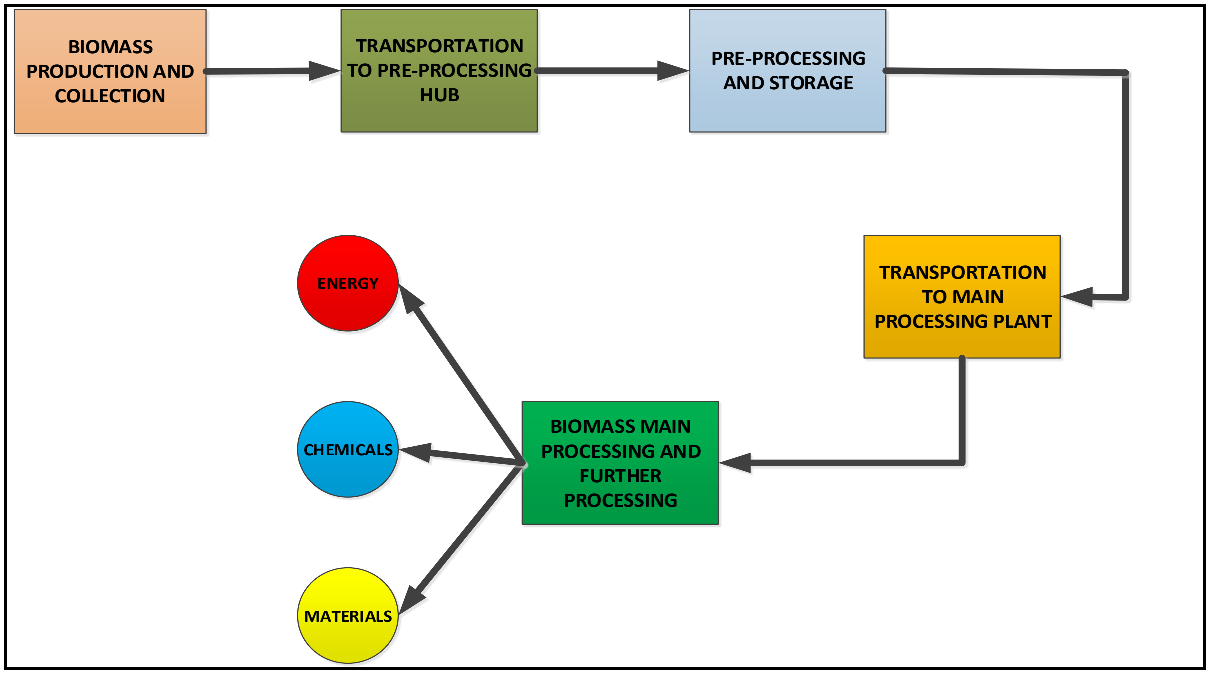

Figure 2.1 Components in biomass supply chain

2.3 Biomass Transportation

Transportation is a major consideration for planning and operation of a biomass project. Transporting biomass in this regard is covered from the farm gate of the producer to the pre-processing hubs and from there to the main processing plants and further processing plants. Minimizing transportation costs are therefore required to gain economic benefits since it can be the limiting factor for financial feasibility. As reported by Oo et al., (2012), transportation costs for biomass is a function of distance, density of the biomass and mode of transportation.

The distances for transporting biomass are determined by the locations of pre-processing site, main processing plant and further processing plant. Since locating processing facilities are vital in reducing biomass transportation costs, several authors have published their works in this area, among of them are You and Wang, (2011), and Bowling et al., (2011). Strictly speaking, to have processing facilities nearby to the biomass resources is a must to ensure overall economic competitiveness.

Biomass density has an important effect in determining transportation cost estimates. Brownell and Liu, (2011) described biomass density as bulk density and energy density. Bulk density is defined as the weight per unit volume of a material, expressed in kilograms per cubic meter (kg/m^3) or pounds per cubic foot (lb/ft^3). Energy density is a term used to describe the amount of energy stored per unit volume, often expressed in MJ/m^3 or BTU/ft^3. A high biomass bulk density can be achieved by removing moisture through drying, while a high biomass energy density is a result of dried biomass plus additional biomass mechanical and thermal processes, called palletization and torrefaction respectively. A higher density of biomass will allow more mass of material to be transported per unit distance. For example, a standard wheat straw bale has a bulk density of about 120 kg/m^3, and a truck with loading volume of 100 m^3 can transport bales weighing approximately 12 tonnes (Oo et al., 2012). The same truck now can transport 580 kg/m^3 of biomass pellets or 800 kg/m^3 of torrefied pellets weighing 40 tonnes or more, subjected to the road load regulations. The cases of lower biomass density typically apply for raw biomass resources from farm gate to the pre-processing site, while the cases of higher biomass density are always possessed by the products from pre-processing facility.

Depending to the distance and load of biomass, typical modes of transportation which include truck, train and barge could be selected. All of these transportation modes need to be evaluated for a case-to-case basis, and have fixed cost components (e.g loading and unloading, capital cost of rail cars, and the marine port) and variable cost components (e.g fuel and operating costs). Truck transport is generally well developed and usually the cheapest mode of transportation but it becomes expensive as travel distance increases, plus it has lowest allowable weight of load compared to train and barge.

2.4 Biomass Pre-processing and Storage

Biomass resources are typically known to have variety of physical and chemical characteristics. These natures are unfavorable for any energy, chemical and material productions projects because they are difficult to transport, as well as they will create unwelcomed operational problems. These facts also somehow become major barriers for widespread uses of biomass as an alternative feedstock to fossil fuels. One of the solutions to overcome this issue is by pre-processing the raw biomass resources so that they are more convenient to carry and at the same time will meet technical specifications of biomass main processes later on. Pre-processing of biomass feedstock in this context can involve pre-treatment, mechanical densification and thermal densification. Depending on the location of biomass feedstock usage, the pre-processing methods can be stand alone or combination of methods.

2.4.1 Pre-treatment

Clarke and Preto (2011) have explained about biomass pre-treatments that include chopping and grinding, drying to required moisture content and applying a binding agent. Chopping and/or grinding are necessary because it will reduce energy use in the densification processes and decrease in breakage of the outcome product. Together with baling, both chopping and grinding processes are normally done at the production fields. Drying of biomass is done to improve its density and durability. As reported by Clarke and Preto (2011), most densification processes require the optimum range of moisture content which in between 8% to 20% on a wet basis. Applying binding agents such as vegetable oil, clay, starch, cooking oil or wax is needed to increase binding properties of densified biomass. Naturally, some biomass sources like corn stalk has high binding properties as compared to warm-season grasses. This difference was due to protein and starch contents.

2.4.2 Mechanical Densification

Basically, the purpose of mechanical densification is to produce densified biomass feedstocks in the form of pellets or briquettes from the loose form of original biomass sources. In this regard, pelletizing and briquetting are the most common processes to densify biomass feedstocks for solid fuels applications (Tumuluru et al., 2010). As these two densification methods involve high pressure compaction technologies, they are also referred as “binderless” technologies. Two common methods are a screw press and a piston press. In a screw press, the biomass is extruded constantly by a screw through a heated taper die that could reduce the friction, while in a piston press, the biomass is punched into a die by a reciprocating ram (Kurchania et al., 2012).

2.4.3 Thermal Densification

The purpose of having thermal densification is to produce torrefied biomass through a process called torrefaction. Torrefaction is a version of pyrolysis (slow pyrolysis) that comprises heating of biomass in the absence of oxygen and air. Besides having very dense biomass materials, another advantage possessed by torrefied biomass is that it has hydrophobic properties (water repellent), making it resistant to biological attack and moisture, thereby facilitating its storage (Clarke and Preto, 2011). This is the superior quality of torrefied biomass as compared to untorrefied biomass pellet and briquette. Having said this, torrefied biomass pellet that combine the characteristics of pelletized and torrefied biomass is the best quality of renewable solid fuel. The density of biomass for selected densification methods is shown in Table 2.1. As for reference, loose biomass has a bulk density of 60-80 kg/m^3 or 3.5-5 lb/ft^3 (Clarke and Preto, 2011).

Table 2.1 Biomass densities according to densification methods (adapted from Clarke and Preto, 2011)

Form of Biomass	Shape and Size Characteristics	Bulk Density (kg/m^3)	Energy Density (GJ/m^3)
Baled biomass	i) Large round, soft core (1.2 x 1.2, 1.2 x 1.5, 1.5 x 1.2, 1.8 x 1.5 m) for diameter x width.	160-190	2.8-3.4
	ii) Large round, hard core (1.2 x 1.2, 1.2 x 1.5, 1.5 x 1.2, 1.8 x 1.5 m) for diameter x width.	190-240	3.4-4.5
	iii) Large/mid-size square (0.6 x 0.9 x 2.4 m)	210-255	3.7-4.7
Briquettes	32 mm diameter x 25 mm thick	350	6.4
Pellets	6.24 mm diameter	550-700	9.8-14.0
Torrefied Pellets	6.24 mm diameter or smaller	800	15.0

2.4.4 Biomass Storage

With the densified biomass feedstocks, they are now ready to be used and can be transported again to main processing site or straight away to the end users. Otherwise, storages are required to temporarily store these densified feedstocks.

According to Williams et al. (2008), there are five types of storage used for agricultural products including i) flat storage, ii) smooth wall steel bins and silos, iii) corrugated steel bins, iv) concrete bins and silos, and v) bunkers. Flat storage comprises of a pre-manufactured metal building or grain piles on the ground covered by a tarp. Smooth wall steel bins are usually used when the quantities of materials to be stored are smaller, while corrugated steel bins will be used when large storage volume is required. Concrete silos are used to be expensive option but recently became attractive due to its durability and because of higher steel price. Bunkers are constructed using timber, steel or cast in place concrete elements, and have disadvantages of high loading and unloading costs. They authors have also mentioned that the economics of biomass storages are depending to the construction costs, durability, throughput and operational costs.

2.5 Biomass Main and Further Processing

Biomass main processing and further processing are converting the pre-processed biomass feedstocks into intermediates and final products. In a conversion plant or usually referred to bio-refinery, biomass inputs must undergo several processing steps depending on the selected conversion technology, which will eventually determine products that are going to be produced. The selection between conversion technologies available or even the consideration within a conversion technology option itself is dictated mainly by techno-economic viability.

As shown in Figure 2.2, biomass conversion technologies are generally can be divided into three main categories; i) thermochemical, ii) chemical, and iii) biochemical processing routes. Further processing is meanwhile will take place after the main processing to further making the derivative products.

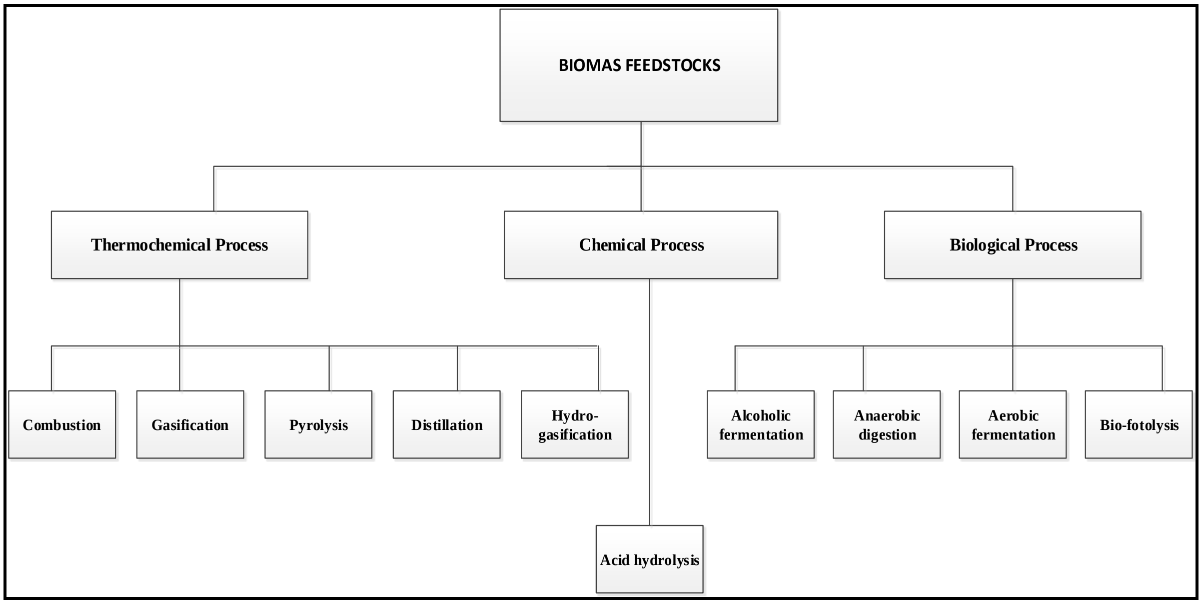

Figure 2.2 Biomass conversion technology routes (adapted from Garcia et al., 2011)

Thermochemical conversion of biomass is a manufacturing platform that apply combustion process to convert the chemical energy stored in biomass into heat (McKendry, 2002). Heat also will be used to break down biomass feeds into an oil-rich vapor in pyrolysis process and synthesis gas in gasification process (Abraham et al., 2003). The following chemical processes (further processing steps) then will convert the intermediate products into an array of products, that analogous to a conventional refinery process. Biomass chemical conversion process path will typically use strong acid to break down lignocellulosic biomass into its single morphological structure whether cellulose, hemicellulose and lignin. Cellulose, hemicellulose and lignin will then undergo further processes to produce ethanol and other liquid fuels (PPD Inc., 2011). Biochemical conversion process path meanwhile will use enzymes of bacteria or other microorganisms to produce energy, chemicals and materials from biomass sources. The biochemical production options are actually will determine the type of products, for instance, alcohol fermentation will produce ethanol, anaerobic digestion will produce biogas, and aerobic fermentation will produce compost (Garcia et al., 2011). The following sub-sections will explain briefly examples of biomass processing processes.

2.5.1 Combustion

Biomass combustion is a thermal process that converts biomass source entirely to carbon dioxide and water vapor, thus precluding conversions to intermediate fuels or chemicals (Abraham et al., 2003). As the main purpose of combustion is to convert chemical energy stored in the fuel into electrical energy, Vanek and Albright (2008) highlighted three key components exist in a power plant that included i) a mean of converting fuel to heat, ii) a mean of converting heat into mechanical energy, and iii) a mean to convert mechanical energy into electrical energy. Figure 2.3 depicts an example of simple biomass combustion process scheme. The energy content of biomass and all other fuels is measured by its heating value. Measurements of heating value can be divided into Gross Heating Value (GHV) and Net Heating Value (NHV). The difference between these two measurements is that GHV will include latent heat of water vapor condensation/vaporization, while NHV will not.

McKendry (2002) has reported that net bio-energy conversion efficiencies for biomass combustion power plants range from 20% to 40%, while a higher efficiency is obtained with systems over 100 MWe or when the biomass is co-combusted in coal-fired power plants. Combined cycle also can improve overall thermal efficiencies as suggested by Vanek and Albright (2008). Apart from the plant efficiency concern, an action to mitigate greenhouse gases from combustion process in the power plant must be urgently done. In Ontario for example, Atikokan generating station with the capacity of 200 MWe has replaced coal as its feedstock with biomass since 2014. This project utilizes 90,000 tonnes of biomass fuels annually and has created 200 jobs during its construction phase (www.opg.com). Biomass fuel has advantages over coal such as higher fuel reactivity due to its high volatile content (Garcia et al., 2011), higher char reactivity, and lower Sulphur content (Demirbas, 2004).

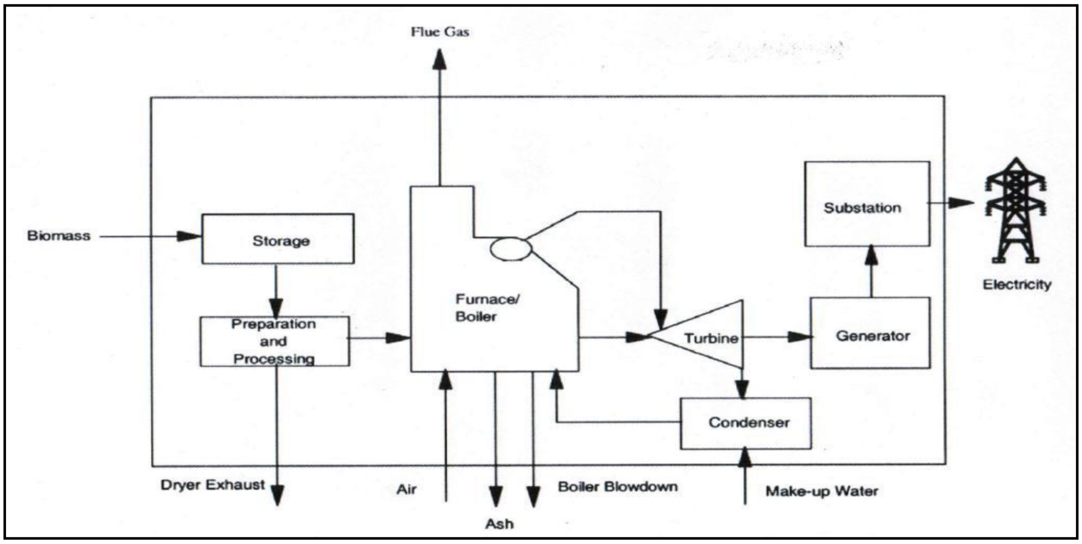

Figure 2.3 Biomass combustion process scheme (adapted from Bain, 2004)

2.5.2 Gasification

Biomass gasification is the conversion of biomass feedstocks by partial oxidation into gaseous product called as synthesis gas or also known as syngas, containing primarily of hydrogen and carbon monoxide, with lesser amounts of carbon dioxide, water, methane, higher hydrocarbons and nitrogen (Ciferno and Marano, 2002). Gasification is considered one of the most efficient ways of converting the energy embedded in biomass, and it is becoming one of the best technological alternatives for solid wastes reuse (Puig-Arnavat et al., 2010). Unlike combustion process, gasification will allow biomass sources to simultaneously become the feedstocks for energy and chemicals productions, the roles that are currently being played by natural gas and other fossil fuels.

For a biomass gasification process, if the desired final products from the syngas are heat and power, a combined heat and power production system as a further processing will be deployed. Otherwise, if the desired final products from the syngas are chemicals and liquid fuels, further processing like methanol production system and Fischer-Tropsch system can be installed, respectively. Table 2.2 shows some applications of syngas in the production of liquid fuels and chemicals.

Table 2.2 Synthesis gas for fuels and chemicals (adapted from Moulijn et al., 2001)

Mixture Ratios	Applications
H_2	Refinery hydro-treating, hydrocracking and emerging uses of hydrogen

$2H_2$:1CO	Alkenes (Fischer-Tropsch reaction)
$2H_2$:1CO	Methanol and higher alcohols productions
$1H_2$:1CO	Aldehydes from hydro-formylation process
CO	Acids (formic and acetic) productions

2.5.3 Pyrolysis

Pyrolysis is the conversion of biomass feedstocks to liquid (also known as bio-oil or bio-crude), solid (bio-char) and gaseous (bio-gas) fractions in the absence of air. This thermochemical conversion process can be divided into fast pyrolysis and slow pyrolysis, which the difference between two is depending on how fast biomass feedstocks are heated relative to the pyrolysis reaction time and the residence time (Basu, 2010). That means, it is considered fast pyrolysis if the time for heating biomass feedstocks to pyrolysis temperature is much faster than the characteristic pyrolysis reaction time, and vice versa. Fast pyrolysis happens at higher heating rate and rapid quenching (shorter residence time) of condensable products, which will predominantly produce bio-oils. Slow pyrolysis meanwhile occurs at lower heating rate and longer residence time that will mainly produce bio-chars. Figure 2.4 depicts a conceptual fast pyrolysis process.

In the production of liquid fuels from bio-oils, selected further processing steps are required to upgrade the fuel properties of bio-oils. McKendry (2002) has reported one of the options for treating and upgrading bio-oils is by hydro-processing that comprises hydro-treating and hydro-cracking. Hydro-treating is used to remove undesired compounds such as oxygen in bio-oil, while hydro-cracking is a process that breaks down larger molecules into naphtha and diesel (You and Wang, 2011).

One clear advantage of pyrolysis and its upgrading scheme is that it is more cost-effective when compared with technologies like biomass gasification with Fischer-Tropsch system (Butler et al., 2012). Bio-char meanwhile is a solid product of biomass pyrolysis that contains unconverted organic solids and carbonaceous residues. Bio-char can be used as a sustainable material for soil amendment because it can sequester carbon in a stable form, improve retention of nutrients and water, and enhance crop yields (Kung et al., 2013).

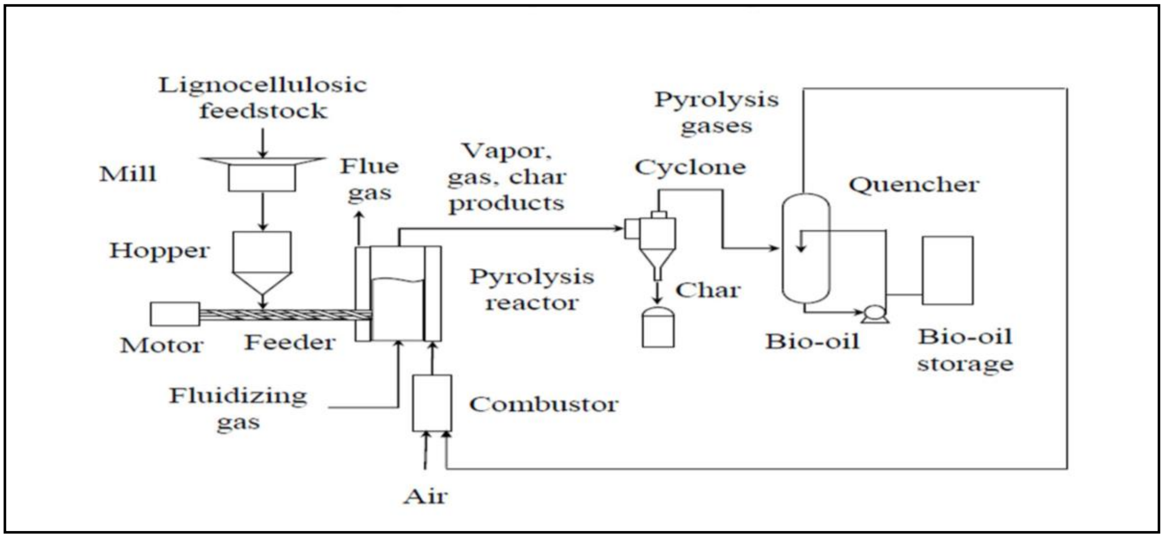

Figure 2.4 A conceptual fast pyrolysis process (source of diagram was from www.biocharfarms.org)

2.5.4 Hydrolysis

According to Verardi et al. (2012), hydrolysis refers to the process of converting the biomass biopolymers into fermentable sugars. In the case of lignocellulosic biomass, cellulose is converted to glucose while hemicelluloses will be broke down into xylose. The lignin remains as by product from extraction. There are two major categories of hydrolysis which the first one uses acid and the second one uses enzyme.

Acid hydrolysis involves exposure of lignocellulosic materials for a period of time at a specific temperature and this produces monomers from cellulose and hemicellulose polymers. Taherzadeh and Karimi (2007) have divided acid hydrolyses into two methods; i) concentrated-acid hydrolysis, ii) dilute-acid hydrolysis. Table 2.3 shows advantages and disadvantages of both methods.

Table 2.3 Comparison between concentrated- and dilute- acid hydrolysis (Taherzadeh and Karimi, 2007)

Hydrolysis method	**Advantages**	**Disadvantages**
Concentrated acid process	- Operated at low temperature (40^{o}C) - High sugar yield (90% of theoretical glucose yield)	- High acid concentration (30-70%) - Equipment damages due to corrosion - High energy consumption for acid recovery
Dilute acid process	- Low acid concentration (0.5%)	- Operated at high temperature (200^{o}c)

	- Short residence time depending to the reactor design	- Degradation of the sugars and formation of undesirable by-products such as furfural, phenol, etc.

As reported by Alvira et al. (2010), main factors that influence the enzymatic hydrolysis in lignocellulosic feedstocks include enzyme-related and substrate-related factors. The enzyme-related factors include lignin-enzyme interaction and the degree of synergy between various enzyme components in the cellulase enzyme mixture. The substrate-related factors are directly connected to the pretreatment that is employed to handle characteristics such as degree of polymerization, crystallinity, substrate's available surface area, lignin barrier and so on. Ling et al. (2013) have added pretreatment processes should be conducted to convert native biomass which is recalcitrant to the enzymatic hydrolysis. An effective pretreatment should be low capital and operational costs as well as able to generate maximum recovery of structural components such as lignin and carbohydrate in a usable form.

2.5.5 Fermentation

Fermentation process can utilize any sugar-containing feedstock to produce ethanol. Gupta and Demirbas (2010) have classified the sugar-containing agricultural raw materials into three categories; i) sugar, ii) starch, and iii) cellulose. The sugars can be directly fermented using yeast to yield ethanol, while starch and cellulose are first converted to sugar by hydrolysis and then fermented. Even though ethanol from cellulose is difficult to obtain at this moment, important factor such as high food and feed prices have influenced decision to proceed with corn-based or sugar-based ethanol. Gupta and Demirbas (2010) have also added that the theoretical amount of ethanol produced per acre of land via corn kernel is much lower than that from lignocellulosic biomass. Figure 2.5 shows overall process scheme for ethanol production from lignocellulosic feedstocks.

2.5.6 Alkaline Activation

Auta et al. (2012) have reported several biomass resources that could be used as activated carbon for removing dyes. These biomass such as coconut husk, coconut shell, rice husk, corncobs, bamboo, saw dust and EFB are eco-friendly, cheaper and renewable adsorbents that potentially could replace expensive coal for production of qualitative and effective activated carbon. In the alkaline activation for producing activated carbon, Auta et al. (2012) carried out an experiment that used potassium hydroxide as an activation agent because of its efficiency and effectiveness in the development of different types of pores and high surface area on carbonaceous materials such as EFB. The produced activated carbon was characterized and tested for performance. Activated carbon that was produced from biomass was capable to remove harmful gas such as hydrogen sulfide with chemical impregnations as reported by Choo et al. (2013).

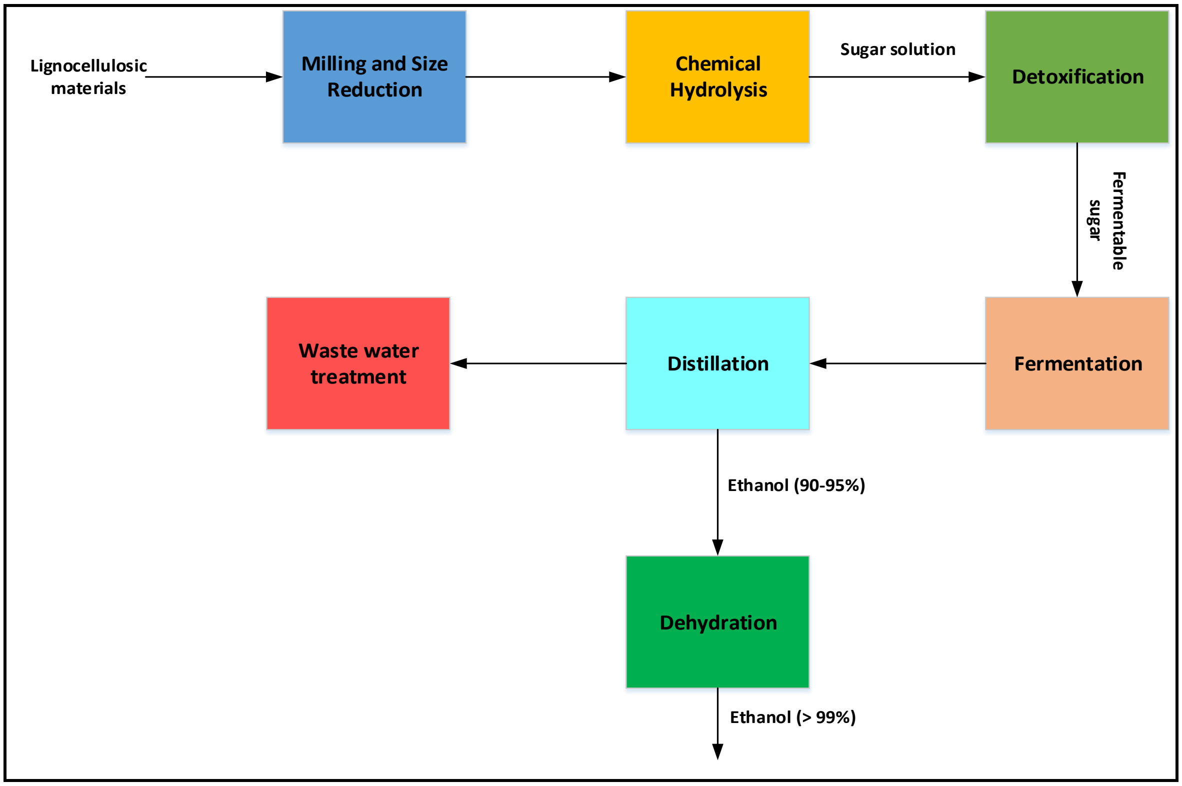

Figure 2.5 Overall process scheme for ethanol production from lignocellulosic feedstocks (adopted from Taherzadeh and Karimi, 2007)

2.5.7 Aerobic Digestion

Aerobic digestion is a biological process in which microbes degrade and stabilize the complex organic compounds of solid biomass to produce composts in the presence of oxygen. The produced compost can be used as fertilizer and soil amendment in garden, landscaping, horticulture and agriculture applications. The process could be done at small-scale which is normally happen at site, or at large-scale commercialized facilities that handle high volumes of organic materials (www.calrecycle.ca.go). These facilities are equipped with sophisticated technologies such as aerated static piles and bio-filters as to meet air quality requirements.

Bustamante et al. (2013) have highlighted benefits of aerobic digestion for compost production that include reductions of odor emissions by decreasing the concentration of volatile compounds, the moisture content, and the potential of photo-toxicity and also could eliminate pathogens. Amira et al. (2011) reported that the use of cellulolytic fungi such as *Apergillus* and *Trichoderma* have shortened the composting process from four months to four weeks. They mixed EFB, palm oil mill effluent (POME) and chicken dung as sources of minerals for the process. Schuchardt and Stichnothe (2010) have added that co-composting of EFB and POME could recover nutrients which decrease the mineral fertilizer demands on plantations.

2.5.8 Anaerobic Digestion

Anaerobic digestion is a biological process that uses microbes to produce biogas under oxygen-free conditions. According to Annamalai et al. (2013), biomass waste is decomposed by two steps, i) breakdown of complex organics by acid-forming bacteria into simpler compounds including volatile acids such as acetic acid and propionic acid, and ii) the conversion of these acids by methane-producing bacteria into methane, CH_4 (~60%) and carbon dioxide, CO_2 (~35%). Zheng et al. (2014) highlighted the anaerobic technology for methane production is a more efficient method for generating energy from biomass compared to other biological and thermos-chemical conversion processes such as cellulosic ethanol. The authors have also stressed that this process also could prevent methane emissions from self-decomposition of biomass in landfills which the methane itself is estimated to be 20 times higher than carbon dioxide in terms of the global warming potential.

There are two basic anaerobic digestion processes which both happen at different temperature ranges (www.biomassenergycentre.org.uk). The first one called as mesophilic digestion that takes places at temperature between 20 – 40^{o}C, and can take up to two months to complete. The second one called as thermophilic digestion that is faster to complete at temperature 50 – 65^{o}C, but the bacteria are more sensitive. In a generalized scheme for anaerobic digester, feedstock is harvested or collected, coarsely shredded, and placed into a reactor which has an active microbes for the methane fermentation. Once produced, the methane will be used as a gaseous fuel.

2.5.9 Dried Long Fiber (DLF) Production

EFB could be used as a renewable feedstock to produce DLF. In the DLF production, it has three steps; i) separation as to fiberize the bulky EFB to produce long strand fibers, ii) drying as to reduce the moisture content until 15% or less, and iii) baling as to compress the DLF in bales (www.ggs.my). The produced DLF can be further processed to produce many products such as mattress, cushion, medium density board, soil erosion mat, bio-composites, and so on.

2.5.10 Bio-composite Production

Bio-composites are composite materials that contain one or more phases derived from a biological origin (Fowler et al., 2006). In this regard, natural fibers such as hemp, flax, jute and kenaf offer positive attributes that include relatively low cost, biodegradable, have good strength and stiffness, and being significantly lighter than conventional reinforcements such as fiber glass (Quarshie and Carruthers, 2014). The matrices may be ideally made from biopolymers but conventional productions are from synthetic polymers such as polyethylene, polypropylene, polystyrene and polyvinyl chloride. Fowler et al. (2006) have added the criteria for selecting suitable fibers were stiffness and tensile strength, elongation at failure, thermal stability, adhesion of fibers and matrices, dynamic and long-term behavior, price and processing cost.

The techniques to manufacture bio-composites are similar to the processes for producing plastics and composites materials such as press molding, injection molding, compounding and extrusion. Applications of bio-composites mainly could be found in automotive, constructions, and buildings.

2.5.11 Bio-resin Production

Bio-resin is a resin or resin formulation that is derived from biological source such as biomass. Due to unsustainable characteristic of phenol-formaldehyde (PF) resins, efforts are intensified to produce the lignin-based resin which is derived from lignocellulosic biomass. Siddiqui (2013) has reported that most research studies have presented successful substitution of petroleum-based phenol with lignin at up to 50% without compromising the resin quality. In addition, lignin also could be used to produce epoxy resin as reported by Sharma et al. (2011) and Ferdosian et al. (2014). The produced bio-resins have numerous applications in coatings, adhesions, and insulations.

2.5.12 Bio-ethylene Production

Ethylene is commercially produced by steam cracking of a wide range of hydrocarbon feedstocks such as ethane, naphtha, gasoil and condensates. As the simplest of olefins, ethylene is used as a base product for many syntheses in the petrochemical industry including productions of plastics, solvents, cosmetics, paints, and packaging (www.technip.com).

For the production of bio-ethylene, it is possible via ethanol or bio-ethanol dehydration process. Zhang and Yu (2013) have reviewed developments in the catalytic ethanol to ethylene production process, catalysts, and reaction mechanisms. In the review, the authors have pointed out that the biomass ethanol dehydration to ethylene process has the edges over the petroleum-based ethylene production based on the followings;

i) The produced bio-ethylene has high purity
ii) The cost for separation and refining of ethylene is very low
iii) The raw materials are easily available for bio-ethanol production
iv) Complex technologies or equipment are not needed, and the process can be easily improved.

Furthermore in 2014, French oil and gas firm Total, IFP Energies Nouvelles and its subsidiary Axens have launched a new technology known as "Atol" which helps the production of bio-ethylene through dehydration of bio-ethanol (www.chemicals-technology.com).

2.6 Previous Optimization Models of Biomass Supply Chain

Edgar et al. (2001) defined optimization as the use of specific methods to determine the most cost-effective and efficient solution to a problem or design for a process. Almost every parts of decision making process has uncertainties and require an assistance of quantitative tool, the area where optimization model plays its significant roles. They also added that motivations for the use of optimization techniques in the chemical industry context were due to several factors such as rise of energy costs, increasingly stringent environmental regulations and global competitiveness in product pricing and quality.

In the case of BSC, optimization model is paramount because of the issues and potentials of biomass utilization system. BSC itself comprises a multi-discipline knowledge and requires inputs from engineering and non-engineering experts. In addition, because of biomass sources may come from any organic matters that differ in term of qualities, a unique approach to manage BSC is required and it is typically a location-sensitive considerations. In order to identify knowledge gaps, Table 2.4 shows previous works on the modeling and optimization of BSC.

Table 2.4 Summary of previous works related to BSC models

Biomass feedstock	**Processing technology**	**Product**	**Type of model***	**Comment**	**Reference**
Switchgrass	Did not mention	Bioethanol	LP	1) Fixed modeling framework and did not account for additional BSC components such as pre-treatment requirement to decrease transportation cost. 2) Did not consider flexibility in determining biomass technological options as well as the desired products produced.	Cundiff et al. (1997)
Wood, energy plants, straw, grass and animal excrements.	Combustion	Heat	MILP	1) Even though the model could simulate inputs of economic and environmental concerns in the future, it was lack of options in representing the true potential of biomass that also can produce products other than heat, for instance, chemicals and materials.	Nagel (2000)
Cotton Stalk	Combustion and CHP	Heat and power	LP	1) The model did not consider heterogeneity of biomass source as well as confined to only one biomass conversion technology	Tatsiopoulus and Tolis (2002)
Wheat straw, corn stover, native prairies, old world bluestem, bermudagrass, tall fescue, and switchgrass.	Gasification and fermentation	Bioethanol	MILP	1) The model did not consider when there were changes in biomass yield and biomass production cost especially when assumption of land-owner willingness to engage in long-term leases was violated. 2) The feasibility of proposed hybrid gasification-fermentation system in handling variety of biomass sources also was the matter of concern	Gelson et al. (2003)

Switchgrass and corn.	Did not mention	Bioethanol	LP	1) Did not consider upstream components of BSC such as biomass production variability, harvesting period, pre-processing requirements, and transportation and handling cost to the conversion plant.	Morrow et al. (2006)
Residues from different types of trees such as almond, cherry, apple, lemon, olive and mandarin.	Did not mention	Bioenergy	LP	1) Did not consider other elements between origin and destination squares such as pre-processing, handling and storage. 2) Did not address biomass potential to produce chemicals or materials.	Perpina et al. (2008)
Corn stover, rice straw, wheat straw, forest straw, forest residue, municipal solid waste (MSW) wood, MSW paper, MSW yard and cotton residue.	Did not mention	Bioethanol	MILP	1) Has yet to consider dynamic aspects of policy standards and conversion technologies, and uncertainties associated with supply/demand, technology, and unexpected disruptions caused by natural and man-made disasters.	Huang et al. (2010)
Corn grain and corn stover.	Fermentation, gasification, catalytic conversion, catalytic dehydration, and cracking.	Bio-ethylene	NLP	1). Did not depict typical BSC system because it only considered investment decision for Biomass to Commodity Chemicals (BTCC) technological options	Cremaschi (2011)
Logging residuals, thinnings, prunings, grasses and chips/shavings.	Fast Pyrolysis and Fischer Tropsch	Gasoline and biodiesel	SP	1). Did not consider uncertainty in terms of product varieties other than energy such as chemicals and materials. 2). The availability of 5 biomass types was changed simultaneously rather than independently in the model.	Kim et al. (2011)

Residues of barley, corn, oats, spring wheat and winter wheat.	Enzymatic hydrolysis and acid hydrolysis	Bioethanol	MILP	1). Did not consider other technological options such as thermochemical and chemical routes, and more homogenous biomass sources such as dedicated crops, and only emphasized on economic performance.	Marvin et al. (2011)
Corn stover, swicthgrass, miscanthus, wood residues (forest residues, primary mills, secondary mills) and urban wood residues	Gasification, pyrolysis and Fischer Tropsch	Gasoline and biodiesel	MOILP	1) Only considered energy products from biomass, and has yet to incorporate different types of uncertainty such as demand fluctuations, biomass supply disruption, and changes in government policies and incentives.	You and Wang (2011)
Oil seed crop	Did not mention	Biodiesel, heat, power, vegetable oil, and syngas	MILP	1) It will become better should the model included the scenario in biomass conversion technological options.	Bowling et al. (2011)
Wood	Did not mention	Bioethanol	SM	1) The simulation model contained a series of assumptions which at one view for model simplification, but from another view did not capture the real practicality. As a result, two types of uncertainties existed in the model; i) data uncertainty and ii) model uncertainty. The author has mentioned that future work will focus on refining the model to consider the both uncertainties.	Zhang et al. (2012)

Wood	Torrefaction	Torrefied wood	Did not mention	1). Beside torrefaction as a mean of biomass pre-processing, it did not consider the overall biomass supply chain for full evaluations of biomass feedstocks for energy, chemicals and materials productions.	Svanberg et al. (2013)
Miscanthus	Did not mention	Bio-ethanol	MILP	1) The biofuel supply chain model that integrates strategic and tactical planning decisions was developed. The key strategic decisions were numbers, locations, capacities, and distribution patterns for biomass and ethanol, while biomass production and delivery were among the tactical decisions. 2) No consideration for multi-products productions from biomass source.	Lin et al. (2014)
Forest residues	Power generation	Bioelectricity	MILP	1) Even though the developed model has yielded results that include optimal selection of biomass sources, plant capacities and transportation modes, it lacked options to produce other bio-products than bioelectricity.	Paulo et al. (2015)

* LP = Linear Programming

MILP = Mixed Integer Linear Programming

NLP = Non-linear Programming

SP = Stochastic Programming

MOILP = Multi-Objective Integer Linear Programming

SM = Simulation Model

Chapter 3

Modeling and Optimization of Biomass to Bio-products Supply Chain: A Research Collaboration with Omtec Incorporated

3.1 Abstract

Supply chain of biomass is one of the major areas that has direct influences towards biomass utilization activities and commercialization progresses. In this chapter, an optimization model of biomass to products supply chain was formulated by considering several cost factors such as biomass cost, production cost and transportation cost. A superstructure that has assisted in the model's formulation provided alternatives in the biomass processing routes which in turn aiming for profit maximization. It has involved a biomass-based manufacturing company in southwestern Ontario which was looking for business expansion and product portfolios' improvements. Optimal results indicated that an annual profit of $ 22,618,673 was expected to be achieved, and this value was contributed mainly by the sales of bio-filler, bio-ethanol and by-product from the milling plant. The developed model offers flexibilities in biomass resources utilization and technological uses.

3.2 Introduction

Biomass is a renewable feedstock for manufacturing products which could be ranged from energy, chemicals and materials. Currently, biomass utilizations are intensified because this bio-resources have abundant supplies, found almost at any places whether in terrestrial or aquatic forms, create wealth and new employments and also offer positive attributes to the sustainability in terms of economic, environmental and societal benefits. Previous works by Sikdar (2003), Clift (2003), and Mata et al. (2011) have reported systematic methodologies to assess those mentioned benefits. In the context of bio-economy meanwhile, biomass are essential processes' feedstocks that will be utilized to produce products via their respective biotechnological routes.

Interconnections between biomass and products entail systematic and efficient flows of the resources to the users, which in this regard called as a supply chain. Various stages exist in the biomass supply chain such as growing, harvesting, transporting, aggregating, and conversion, which each stage require unique sets of knowledge, technology and activity (WGBN, 2015). Growing is an activity that provides adequate biomass resources for utilizations. These resources may origin from forestry (wood, sawdust, bark, and chips), agricultural residues (wheat straw, soybean stalk, oil palm empty fruit bunch, rice husk, shrimp shell, and animal manure) as well as dedicated crops (switchgrass, sorghum, miscanthus, jatropha, algae, and fungi). All of the plant based origins that have been mentioned are categorized as lignocellulosic biomass. Biomass harvesting and field collection are activities to remove and collect the resources from the fields, which practices are subjected to type of biomass and its final uses (Bioenergyconsult, 2015). The harvest window for agricultural residues is the time between the grain harvest and the next field operation such as tilling and cover crop's planting (Hettenhaus et al., 2011). Biomass is then collected and baled for transportation. Transporting the biomass feedstocks begin from the farm gate to the aggregating and pre-processing facilities. As reported by Oo et al. (2012), transportation cost for biomass is a function of distance, bulk density of the biomass and mode of transportation.

At the pre-processing facilities, biomass feedstocks are first treated before sending them to the main processing facilities. The strategies on how to pre-process the feedstocks will have direct impacts the bio-product yields, as well as the capital and operating costs of the downstream processes. Saville et al. (2011) have reported that pre-processing can be divided into three broad categories, i) mechanical process that primarily reduce the size of incoming biomass feedstock, ii) chemical process that depend on the uses of acids, bases, solvents, or other bio-agents for extracting select components of the feedstock, or for structure modification, and iii) thermomechanical or thermochemical processes that require a combination of heat, pressure, and mechanical energy to alter the biomass feedstock. Biomass conversions happen at main processing facilities, always referred as bio-refineries. In these facilities, as an analogy to petro-refineries, pre-processed biomass feedstocks are refined to produce numerous value-added bio-products in fulfilling the market demands. Technological selections at this stage, whether thermochemical, chemical, or biochemical routes are mainly dictated by the syntheses and economic viabilities. For this chapter, of the whole biomass supply chain's stages that were explained, the analysis will only involve pre-processing and downstream processing facilities, storages and transportations.

The biomass supply chain plays important roles in any biomass utilization project. It is because the supply chain is one the key considerations for determining project's successfulness. Having said that, improper design of biomass supply chain will amplify intrinsic issues such as competing uses of biomass feedstocks, supply of biomass feedstocks with acceptable qualities, available technological options to convert biomass feedstocks into saleable bio-products, as well as mobilization of biomass from scattered locations to nearby processing hubs. When dealing with these biomass supply chain issues, it is not uncommon for a biomass-based manufacturing company to face decision dilemma, as shown by question marks in Figure 3.1. Four scenarios are identified to exist in any biomass's utilization project, and they are a) single feedstock for single bio-product, b) multiple feedstocks for single bio-product, c) single feedstock for multiple bio-products, and d) multiple feedstock for multiple bio-products. For scenario a), main decision should be made to select the best available biomass type to produce the desired bio-product within the correct economy of scale. For example, corn is planted, harvested and processed to produce bio-ethanol that has high market demands for gasoline blending. However, lingo-cellulosic biomass such as switchgrass is another option for feedstock to produce the same bio-product, i.e bio-ethanol. Here, judgements on whether to use corn or switchgrass for bio-ethanol production must be based on detail analysis to prevent unwelcome problems such as prices rise because more corns are used to produce energy rather than for foods or feeds. In b), multiple biomass feedstocks are potentially to be utilized to produce single bio-product which is normally has high demands and limited supplies. For example, cellulose is produced to manufacture its derivatives such as carboxymethyl cellulose (CMC), hydroxyethyl cellulose (HEC), cellulose acetate, nitrocellulose, nanofibrillated cellulose (NFC), nanocrystalline cellulose (NCC), and cellulose filaments. Each derivative has its own residential, commercial or industrial applications. Basically, every lignocellulosic feedstocks could be utilized to produce cellulose. However, decision variables exist on how to use those feedstocks, whether they could be blended all together to achieve homogenous qualities or not. In addition, technological selections dilemma also exists such as mechanical vs chemical process, strong vs weak acidic pre-treatment, and so on.

Scenario c) is similar to current petro-refinery process where crude oil is refined to produce different kind of products such as naphtha, liquefied petroleum gas (LPG), gasoline, diesel, kerosene, bitumen, and etc. Here, ability to make decision in dynamic market situations of those products is critical. Scenario d) deals with multiple feedstocks for multiple products. In this scenario, more complex decisions have to be made to determine the best combinations of feedstocks, technologies and products out of available options. In practice, this scenario might relevant to multiple owners that own their separate bio-refineries in an integrated manufacturing complex or a single owner that facilitates several bio-refineries under its subsidiaries.

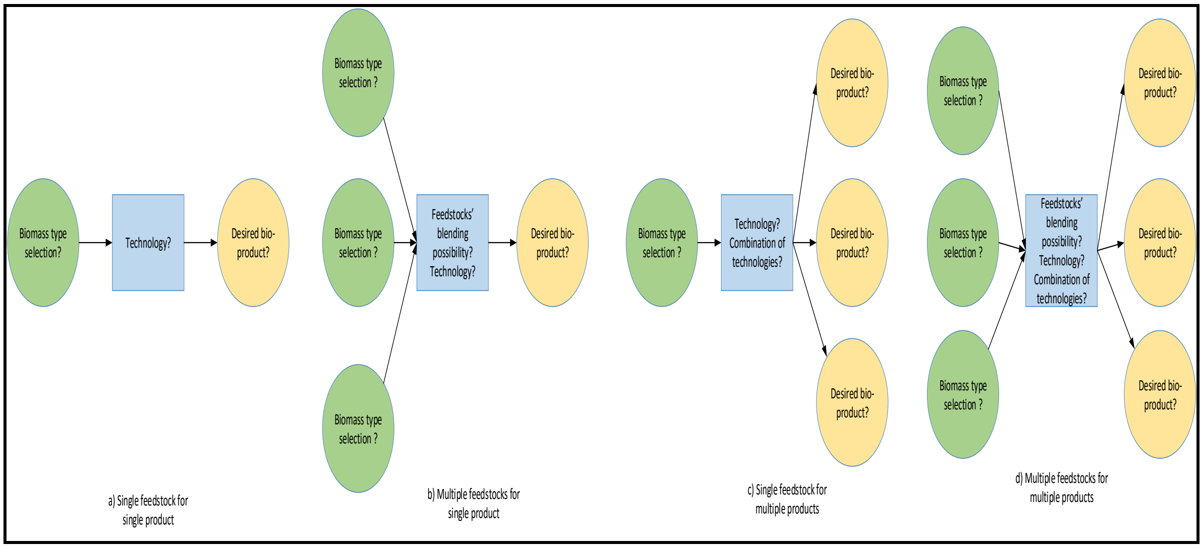

Figure 3.1 Four scenarios and decision dilemma in utilizing biomass resources to produce bio-products

In solving those decision dilemmas, it is imperative at this points to have a systematic tool for the decision making process. Optimization technique is hence required to provide the best solution out of possible options available. In this chapter, the technique has involved with modeling and optimization of biomass supply chain to produce multiple bio-products from multiple biomass feedstocks. Modeling and optimization of biomass supply chain and bio-refineries planning have been studied by several authors. Cucek et al. (2010) have synthesized networks for the supply of energy and bio-products using mixed integer linear programming (MILP) model. The developed model have considered multiple technologies for the productions of energy and food, with the former was more economically favourable to produce. Gutierrez-Arriaga et al. (2012) have developed a multi-objective optimization model of steam power plants for sustainable electricity generation in which biomass was among the primary energy sources used. It has considered both economic and environmental performances. Multivariable economic optimization model has been developed by Sukumara et al. (2013) to produce biofuels from biomass. The methodology has combined models from different fields of knowledge to provide informed decision. Jiang et al. (2015) introduced a green vendor-managed inventory (VMI) that involved with carbon trading mechanism. The total cost of the supply chain between supplier and manufacturer could increase which was subjected to specific set of parameters.

The goal in this chapter was to develop an integrated Linear Programming (LP) optimization model of biomass supply chain for Omtec Inc. in Ridgetown, Ontario. The company is currently producing bio-filler from wheat straw for automotive industry, would expect to expand its bio-product portfolios that range from energy, chemicals and materials. They wanted to have flexibilities in biomass feedstock usages and possibilities of feedstocks' blending for sustainable supplies. Hence, scenario d) in Figure 3.1 was relevant in this case. Since it was a company specific optimization model, an integrated layer of processing facilities and the corresponding products were predetermined, and have suited the company's operating parameters and constraints.

3.3 Methodology

Methodology for this chapter is shown in Figure 3.2. In formulating a model to optimize the supply chain, diagram that serves as a modeling guideline, here is referred as "superstructure" was first constructed by considering all inputs from the company. As shown in Figure 3.3, five layers of processing facilities and storages for the proposed products are connected in stages, which represent the actual supply chain. Biomass a, Biomass b, and Biomass c, were named in such way to probably represent three sources of wheat straws with different qualities or three type of biomass sources such as wheat straw, corn stover and soybean stalk. Description of indices in Figure 3.3 and the ones that would be used in the formulation was shown in Table 3.1. Please note that there are also options to sell the produced bio-products at that particular stages, instead of sending them for next processing. Furthermore, the route to extract nutrients from biomass feedstocks even though was shown in the superstructure was still under consideration. Hence, this chemical route was omitted in the analysis.

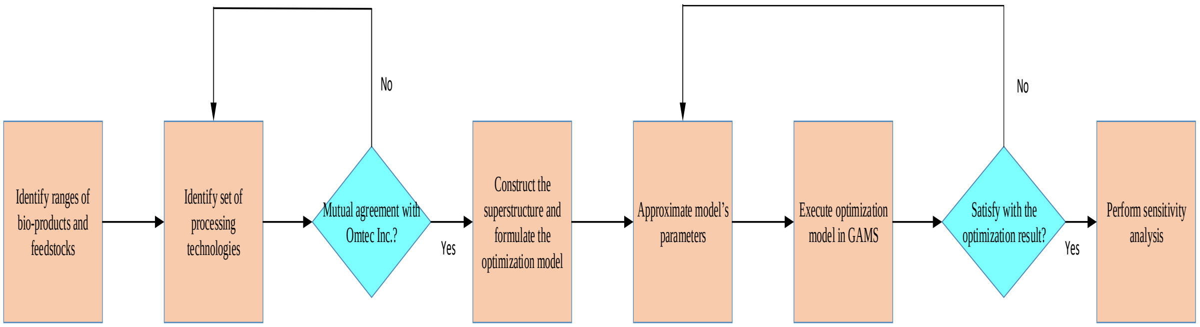

Figure 3.2 Methodology for Chapter 3

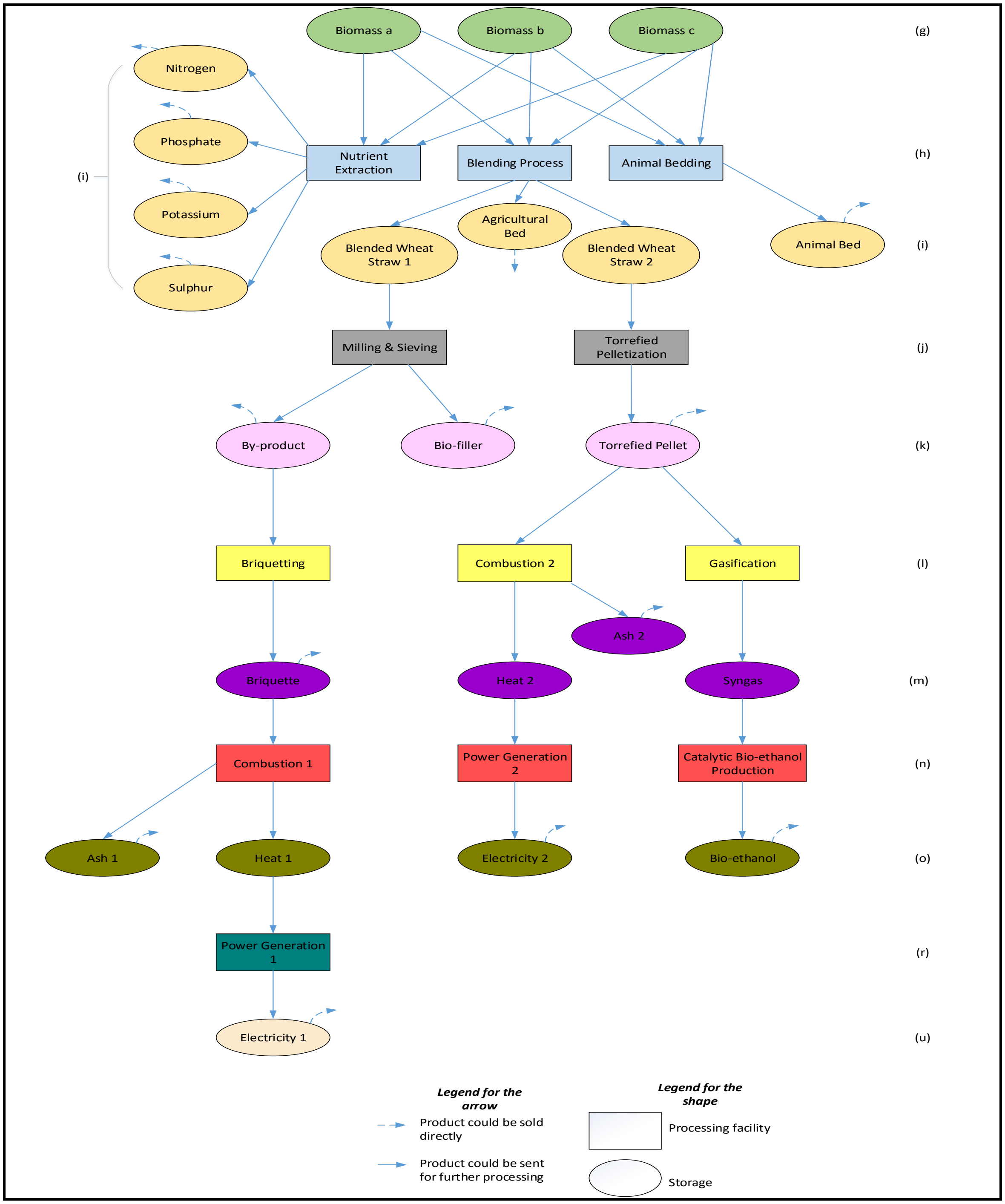

Figure 3.3 A superstructure of biomass to bio-products supply chain

Table 3.1 List of indices and descriptions in the biomass to bio-products supply chain's superstructure

Indices	Descriptions	Contents
g	Biomass resources at delivery locations	Biomass a, biomass b, and biomass c.
h	Pre-processing facilities	Nutrient extraction, blending process, and animal bedding.
i	Pre-processed products	Blended wheat straw1, blended wheat straw2, agricultural bed, animal bed, nitrogen, phosphate, potassium and sulphur.
j	Processing one facilities	Milling & sieving and torrefied pelletization.
k	Processed one products	Bio-filler, torrefied pellet, and by-product.
l	Processing two facilities	Briquetting, combustion2, and gasification
m	Processed two products	Briquette, heat2, ash2, and syngas.
n	Processing three facilities	Combustion1, power generation2, and catalytic bio-ethanol production
o	Processed three products	Ash1, heat1, electricity2, and bio-ethanol
r	Processing four facility	Power generation1
u	Processed four product	Electricity1
p	Summation of all products	Blended wheat straw1, blended wheat straw2, agricultural bed, animal bed, nitrogen, phosphate, potassium, sulphur, bio-filler, torrefied pellet, by-product, briquette, heat2, ash2, syngas, Ash1, heat1, electricity2, bio-ethanol, and electricity1

The developed model has aimed for annual profit maximization of overall layers of technologies and bio-products by considering associated costs such as biomass cost, production cost and transportation cost. The biomass cost was the total purchase cost of biomass feedstocks that received at aggregation hubs. These hubs serve as delivery points to the pre-processing facilities. The production cost was the cost to produce one unit capacity of product. Further explanations and accurate calculations about this cost can be found from Mani et al. (2006). The transportation costs have involved with every connecting point between processing stages as well as from product storage to the respective customer.

All of the costs and other model's parameters were approximated from literatures and personal communications with Mr. Jim Kozlowski, the Omtec's R&D Manager. The model has intended to provide ranges of bio-products and ranked them according to their contributions to the overall annual profit. Optimal solution was found by using GAMS.

3.4 Problem Formulation and Parameter Approximation

In the model's formulation, economic efficiency of the biomass supply chain was the objective function. It was indicated by annual profitability that was optimized by considering sales of bi-products and the associated costs. In searching for optimal solution, the model has considered evaluations of different processing routes, and hence different technologies for making bio-products at the same time.

Mathematical model that contain the objective function's details are shown by (3.1) till (3.5). Meanwhile, (3.6) till (3.23) represent the model's mass balances and constraints. Altogether, explanations for each formulation were tabulated in Table 3.2. Following that table, each term in all of those formulations was explained in Table 3.3.

Maximize Profit ($/year) = Max (Sales of Products - Biomass Cost - Transportation Cost - Processing Cost) (3.1)

$$\textit{Sales of Products} = \sum_{p=1}^{P} Q_p * Products'\ Selling\ Price \tag{3.2}$$

$$Biomass\ Cost = \sum_g^G F_g * Biomass\ Received\ Cost \tag{3.3}$$

$$\begin{aligned} Transportation\ Cost = {} & \left(\sum_g^G \sum_h^H FTRPF_{g,h} * TRCGH_{g,h}\right) + \left(\sum_h^H \sum_i^I FTRSH_{h,i} * TRCHI_{h,i}\right) + \\ & \left(\sum_h^H \sum_i^I \sum_j^J FTRPH_{h,i,j} * TRCHIJ_{h,i,j}\right) + \left(\sum_j^J \sum_k^K FTRSJ_{j,k} * TRCJK_{j,k}\right) + \left(\sum_j^J \sum_k^K \sum_l^L FTRPJ_{j,k,l} * \right. \\ & \left. TRCJKL_{j,k,l}\right) + \left(\sum_l^L \sum_m^M FTRSL_{l,m} * TRCLM_{l.m}\right) + \left(\sum_l^L \sum_m^M \sum_n^N FTRPL_{l,m,n} * TRCLMN_{l,m,n}\right) + \\ & \left(\sum_n^N \sum_o^O FTRSN_{n,o} * TRCNO_{n,o}\right) + \left(\sum_n^N \sum_o^O \sum_r^R FTRPN_{n,o,r} * TRCNOR_{n,o,r}\right) + \left(\sum_r^R \sum_u^U FTRSR_{r,u} * \right. \\ & \left. TRCRU_{r,u}\right) \end{aligned} \tag{3.4}$$

$$\begin{aligned} Production\ Cost = {} & \left(\sum_h^H \sum_i^I FPRDH_{h,i} * PRODCH_{h,i}\right) + \left(\sum_i^I \sum_j^J \sum_k^K FPRDJ_{i,j,k} * PRODCJ_{i,j,k}\right) + \\ & \left(\sum_k^K \sum_l^L \sum_m^M FPRDL_{k,l,m} * PRODCL_{k,l,m}\right) + \left(\sum_m^M \sum_n^N \sum_o^O FPRDN_{m,n,o} * PRODCN_{m,n,o}\right) + \\ & \left(\sum_o^O \sum_r^R \sum_u^U FPRDR_{o,r,u} * PRODCR_{o,r,u}\right) \end{aligned} \tag{3.5}$$

$$\sum_h^H FTRPF_{g,h} \leq F_g \qquad \forall_g \tag{3.6}$$

$$\sum_g^G FTRPF_{g,h} * CONVH_{h,i} = FPRDH_{h,i} \qquad \forall_{h,i} \tag{3.7}$$

$$FPRDH_{h,i} = \sum_{j}^{J} FTRPH_{h,i,j} + FTRSH_{h,i} \qquad \forall_{h,i} \tag{3.8}$$

$$\sum_{h}^{H} FTRPH_{h,i,j} * \ CONVJ_{i,j,k} = FPRDJ_{i,j,k} \qquad \forall_{i,j,k} \tag{3.9}$$

$$\sum_{i}^{I} FPRDJ_{i,j,k} = FTRSJ_{j,k} + \sum_{l}^{L} FTRPJ_{j,k,l} \qquad \forall_{j,k} \tag{3.10}$$

$$\sum_{j}^{J} FTRPJ_{j,k,l} * \ CONVL_{k,l,m} = FPRDL_{k,l,m} \qquad \forall_{k,l,m} \tag{3.11}$$

$$\sum_{k}^{K} FPRDL_{k,l,m} = \ FTRSL_{l,m} + \ \sum_{n}^{N} FTRPL_{l,m,n} \qquad \forall_{l,m} \tag{3.12}$$

$$\sum_{l}^{L} FTRPL_{l,m,n} * CONVN_{m,n,o} = FPRDN_{m,n,o} \qquad \forall_{m,n,o} \tag{3.13}$$

$$\sum_{m}^{M} FPRDN_{m,n,o} = FTRSN_{n,o} + \sum_{r}^{R} FTRPN_{n,o,r} \qquad \forall_{n,o} \tag{3.14}$$

$$\sum_{n}^{N} FTRPN_{n,o,r} * CONVR_{o,r,u} = \ FPRDR_{o,r,u} \qquad \forall_{o,r,u} \tag{3.15}$$

$$\sum_{o}^{O} FPRDR_{o,r,u} = FTRSR_{r,u} \qquad \forall_{r,u} \tag{3.16}$$

$$\sum_{h}^{H} FTRSH_{h,i} + \ \sum_{j}^{J} FTRSJ_{j,k} + \ \sum_{l}^{L} FTRSL_{l,m} + \ \sum_{n}^{N} FTRSN_{n,o} + \sum_{r}^{R} FTRSR_{r,u} = Q_p \qquad \forall_{i,k,m,o,u} \tag{3.17}$$

$$F_g \ \leq Biomass\ Availability_g \qquad \forall_{g} \tag{3.18}$$

$$Q_p \geq Produced\ Products'Demand_p \qquad \forall_{p} \tag{3.19}$$

$$FTRPH('BLENDING - PROCESS','\ AGRICULTURAL - MULCH', j) = e = 0 \tag{3.20}$$

$$FTRPH('BLENDING - PROCESS','\ ANIMAL - BED', j) = e = 0 \tag{3.21}$$

$$FTRPL('COMBUSTION2','ASH2', n) = e = 0 \tag{3.22}$$

$$FTRPN('COMBUSTION1','\ ASH1', r) = e = 0 \tag{3.23}$$

Table 3.2 Description of mathematical formulations in Chapter 3

Formulation	Description
(3.1)	Objective function and profit equation in $/year

(3.2)	Sales of products (revenue) in $/year
(3.3)	Biomass resource cost in $/year
(3.4)	Costs associated in transporting biomass and produced products in $/year
(3.5)	Costs associated in processing biomass and produced products in $/year
(3.6)	Mass balance for biomass resources at delivery locations, *g* in tonne/year
(3.7)	Mass balance for yield of pre-processed products, *i* in tonne/year
(3.8)	Mass balance for pre-processing facilities outlets, *h* in tonne/year
(3.9)	Mass balance for yield of processed one products, *k* in tonne/year
(3.10)	Mass balance for processing one facilities outlets, *j* in tonne/year
(3.11)	Mass balance for yield of processed two products, *m* in tonne/year
(3.12)	Mass balance for processing two facilities outlets, *l* in tonne/year
(3.13)	Mass balance for yield of processed three products, *o* in tonne/year or kWh/year
(3.14)	Mass balance for processing three facilities outlets, n in tonne/year or kWh/year
(3.15)	Mass balance for yield of final product, *u* in kWh/year
(3.16)	Mass balance for processing four facilities outlets, r in kWh/year
(3.17)	Summation of sales for produced products in tonne/year
(3.18)	Mass balance of biomass resources at delivery locations must be less or equal than total biomass resources availabilities in tonne/year
(3.19)	Mass balance of produced product must be higher or equal than its demand requirement in tonne per year
(3.20)	Constraint to ensure agricultural mulch is entirely sold to the customer
(3.21)	Constraint to ensure animal bed is entirely sold to the customer
(3.22)	Constraint to ensure ash2 is entirely sold to the customer
(3.23)	Constraint to ensure ash1 is entirely sold to the customer

Table 3.3 Descriptions of terms used in (3.1) till (3.23)

Term	Category	Description
$TRCGH_{g,h}$	Parameter	Transportation cost factor for biomass resources from g to h in $ per tonne.
$TRCHIJ_{h,i,j}$	Parameter	Transportation cost factor for pre-processed products, i from h to j in $ per tonne.
$TRCHI_{h,i}$	Parameter	Transportation cost factor for pre-processed products, i that may be sold directly in $ per tonne.
$TRCJKL_{j,k,l}$	Parameter	Transportation cost factor for processed one products, k from j to l in $ per tonne.
$TRCJK_{j,k}$	Parameter	Transportation cost factor for processed one products, k that may be sold directly in $ per tonne.
$TRCLMN_{l,m,n}$	Parameter	Transportation cost factor for processed two products, m from l to n in $ per tonne.
$TRCLM_{l.m}$	Parameter	Transportation cost factor for processed two products, m that may be sold directly in $ per tonne.
$TRCNOR_{n,o,r}$	Parameter	Transportation cost factor for processed three products, o from n to r in $ per tonne.
$TRCNO_{n,o}$	Parameter	Transportation cost factor for processed three products, o that will be sold directly in $ per tonne/kWh
$TRCRU_{r,u}$	Parameter	Transportation cost factor for final product, u that will be sold in kWh per year.
$PRODCH_{h,i}$	Parameter	Production cost factor at h to produce i from g in $ per tonne.
$PRODCJ_{i,j,k}$	Parameter	Production cost factor at j to produce k from i in $ per tonne.
$PRODCL_{k,l,m}$	Parameter	Production cost factor at l to produce m from k in $ per tonne.
$PRODCN_{m,n,o}$	Parameter	Production cost factor at n to produce o from m in $ per tonne.

$PRODCR_{o,r,u}$	Parameter	Production cost factor at r to produce u from o in $ per tonne.
$CONVH_{h,i}$	Parameter	Conversion factor at h to produce i.
$CONVJ_{i,j,k}$	Parameter	Conversion factor at j to produce k from i.
$CONVL_{k,l,m}$	Parameter	Conversion factor at l to produce m from k.
$CONVN_{m,n,o}$	Parameter	Conversion factor at n to produce o from m.
$CONVR_{o,r,u}$	Parameter	Conversion factor at r to produce u from o.
$Products'\ Selling\ Price$	Parameter	Selling price of produced products
$Biomass\ Received\ Cost$	Parameter	Cost to purchase biomass resources
$Biomass\ Availability$	Parameter	Total biomass resources availabilities
$Produced\ product's\ Demand$	Parameter	The demand for produced products
Q_p	Decision variable	Amount of produced products, p in tonne or kWh per year.
F_g	Decision variable	Amount of biomass resources ready at delivery location in tonne per year.
$FTRPF_{g,h}$	Decision variable	Amount of biomass transported to pre-processing facilities, h in tonne per year.
$FTRPH_{h,i,j}$	Decision variable	Amount of pre-processed products, i transported from pre-processing facilities, h to processing one facilities, j in tonne per year.
$FTRSH_{h,i}$	Decision variable	Amount of pre-processed products, i produced from pre-processing facilities, h that may be sold directly in tonne per year.
$FTRPJ_{j,k,l}$	Decision variable	Amount of processed one products, k transported from processing one facilities, j to processing two facilities, l in tonne per year.
$FTRSJ_{j,k}$	Decision variable	Amount of processed one products, k produced from processing one facilities, j that may be sold directly in tonne per year.

$FTRPL_{l,m,n}$	Decision variable	Amount of processed two products, *m* transported from further processing two facilities, *l* to processing three facilities, *n* in tonne per year.
$FTRSL_{l,m}$	Decision variable	Amount of processed two products, *m* produced from further processing two facilities, *l* that may be sold directly in tonne per year.
$FTRPN_{n,o,r}$	Decision variable	Amount of processed three products, *o* transported from further processing three facilities, *n* to processing four facility, *r* in tonne per year.
$FTRSN_{n,o}$	Decision variable	Amount of processed three products, *o* produced from further processing three facilities, *n* that will be sold directly in tonne/kWh per year.
$FTRSR_{r,u}$	Decision variable	Amount of final product, *u* produced from processing four facilities, *r* will be sold in kWh per year.
$FPRDH_{h,i}$	Decision variable	Amount of pre-processed products, *i* produced from biomass resources, *g* through pre-processing facilities, *h* in tonne per year.
$FPRDJ_{i,j,k}$	Decision variable	Amount of processed one products, *k* produced from pre-processed products, *i* through processing one facilities, *j* in tonne per year.
$FPRDL_{k,l,m}$	Decision variable	Amount of processed two products, *m* produced from processed one products, *k* through processing two facilities, *l* in tonne per year.
$FPRDN_{m,n,o}$	Decision variable	Amount of processed three products, *o* produced from processed two products, *m* through further processing three facilities, *n* in tonne per year.
$FPRDR_{o,r,u}$	Decision variable	Amount of final product, *u* produced from processed three products, *o* through processing four facilities, *r* in tonne per year.

Some of the terms in Table 3.3 were categorized as model's parameters. These have included transportation cost factor, production cost factor, conversion factor, product's selling price, biomass's received cost, biomass's availability and bio-product's demand. All of these parameters were the determining factors and have influenced the optimal solution's value and status. In order to demonstrate the model's practicality, approximation of parameters were done and believed to be adequate for that purpose. Furthermore, it was difficult to obtain actual data for parameters due to several factors such as difference in operation scales, stages of commercial biomass utilizations and availabilities of simulation models for specific technologies. Having said that, the obtained optimal result was subjected to the qualities and availabilities of those approximated parameters. Table 3.4 till 3.26 tabulate all of the parameters that were used in the optimization model. Each of the table has reference for the approximations.

Table 3.4 Approximated transportation cost factor for biomass resources from g to h, $(TRCGH_{g,h})$ in $ per tonne (Oo et al.,2012)

Origin (*g*)	**Destination (*h*)**	**Distance (km)**	**Pre-determined transportation mode**	**Transportation cost factor ($/tonne)**
Biomass a	Nutrient Extraction	50	Truck	15.05
Biomass a	Blending Process	70	Truck	18.33
Biomass a	Animal Bedding	55	Truck	15.87
Biomass b	Nutrient Extraction	60	Truck	16.69
Biomass b	Blending Process	65	Truck	17.51
Biomass b	Animal Bedding	75	Truck	19.15
Biomass c	Nutrient Extraction	80	Truck	19.97
Biomass c	Blending Process	85	Truck	20.79
Biomass c	Animal Bedding	75	Truck	19.15

Table 3.5 Approximated transportation cost factor for pre-processed products, *i* from h to j $(TRCHIJ_{h,i,j})$ in $ per tonne (Oo et al., 2012)

Origin (*h*)	**Destination (*j*)**	**Distance (km)**	**Pre-determined transportation mode**	**Transportation cost factor ($/tonne)**
Blending Process	Torrefied Pelletization	2	Truck	7.17
Blending Process	Milling & Sieving	3	Truck	7.33

Table 3.6 Approximated transportation cost factor for pre-processed products, i that may be sold directly $(TRCHI_{h,i})$ in $ per tonne (Oo et al., 2012)

Origin (*h*)	**Pre-processed feedstock (*i*)**	**Customer destination**	**Distance (km)**	**Pre-determined transportation mode**	**Transportation cost factor ($/tonne)**
Animal Bedding	Animal Bed	C5	50	Truck	15.05

Blending Process	Agricultural Mulch	C6	55	Truck	15.87

Table 3.7 Approximated transportation cost factor for processed one products, *k* from j to l ($TRCJKL_{j,k,l}$) in $ per tonne (Oo et al., 2012)

Origin (*j*)	**Destination (*l*)**	**Distance (km)**	**Pre-determined transportation mode**	**Transportation cost factor ($/tonne)**
Milling & Sieving	Briquetting	4	Truck	7.49
Torrefied Pelletization	Combustion 2	7	Truck	7.99
Torrefied Pelletization	Gasification	5	Truck	7.66

Table 3.8 Approximated transportation cost factor for processed one products, *k* that may be sold directly
($TRCJK_{j,k}$) in $ per tonne (Oo et al., 2012)

Origin (*j*)	**Intermediate product 1 (*k*)**	**Customer destination**	**Distance (km)**	**Pre-determined transportation mode**	**Transportation cost factor ($/tonne)**
Milling & Sieving	Bio-filler	C7	367	Truck	67.06
Milling & Sieving	By-product	C8	35	Truck	12.58
Torrefied Pelletization	Torrefied Pellet	C9	53	Truck	15.54

Table 3.9 Approximated transportation cost factor for processed two products, *m* from *l* to *n* ($TRCLMN_{l,m,n}$) in $ per tonne (Oo et al.,2012 and Blok et al., 1995)

Origin (*l*)	**Destination (*n*)**	**Distance (km)**	**Pre-determined transportation mode**	**Transportation cost factor ($/tonne)**
Briquetting	Combustion 1	4.0	Truck	7.50
Combustion 2	Power Generation 2	0.7	Pipe	0.04
Gasification	Catalytic Bio-ethanol Production	0.5	Pipe	0.03

Table 3.10 Approximated transportation cost factor for processed two products, *m* that may be sold directly
($TRCLM_{l,m}$) in $ per tonne (Oo et al., 2012)

Origin (*l*)	**Intermediate product 2 (*m*)**	**Customer destination**	**Distance (km)**	**Pre-determined transportation mode**	**Transportation cost factor ($/tonne)**
Combustion 2	Ash 2	C10	30	Truck	11.76
Briquetting	Briquette	C11	75	Truck	19.15

Table 3.11 Approximated transportation cost factor for processed products three, o from n to r ($TRCNOR_{n,o,r}$) in $ per tonne (Blok et al., 1995)

Origin (*n*)	Destination (*r*)	Distance (km)	Pre-determined transportation mode	Transportation cost factor ($/tonne)
Combustion 1	Power Generation 1	1	Pipe	0.05

Table 3.12 Approximated transportation cost factor for processed three products, o that will be sold directly ($TRCNO_{n,o}$) in $ per tonne/kWh (Oo et al., 2012, Blok et al.1995 and ialtenergy, 2015)

Origin (*n*)	Intermediate product 3 (*o*)	Customer destination	Distance (km)	Pre-determined transportation mode	Transportation cost factor ($/kWh or $/tonne)
Power Generation 2	Electricity 2	C12	-	Transmission Grid	0.02
Combustion 1	Ash 1	C13	25	Truck	10.94
Catalytic Bio-ethanol Production	Bio-ethanol	C14	2	Pipe	0.10

Table 3.13 Approximated transportation cost factor for final product, u that will be sold ($TRCRU_{r,u}$) in kWh per year (ialtenergy, 2015)

Origin (*r*)	Final product (*u*)	Customer destination	Distance (km)	Pre-determined transportation mode	Transportation cost factor ($/kWh)
Power Generation 1	Electricity 1	C15	-	Transmission Grid	0.02

Table 3.14 Approximated production cost factor at h to produce i from g ($PRODCH_{h,i}$) in $ per tonne (Kozlowski, 2015)

Feedstock (*g*)	Process (*h*)	Product (*i*)	Production cost factor ($ per tonne of product)
Biomass (a,b, or c)	Nutrient Extraction	Nitrogen, Phosphate, Potassium, and Sulphur	NA
Biomass (a,b, or c)	Animal Bedding	Animal Bed	77.16
Biomass (a,b, or c)	Blending Process	Blended Biomass 1 or 2	10.00
Biomass (a,b, or c)	Blending Process	Agricultural mulch	0.00

Table 3.15 Approximated production cost factor at j to produce k from i ($PRODCJ_{i,j,k}$) in $ per tonne (Kozlowski, 2015 and O'Malley, 2013)

Feedstock (*i*)	Process (*j*)	Product (*k*)	Production cost factor ($ per tonne of product)
Blended Biomass a	Milling & Sieving	Bio-filler	330.69
Blended Biomass b	Milling & Sieving	By-product	0.00
Blended Biomass c	Torrefied Pelletization	Torrefied Pellet	78.00

Table 3.16 Approximated production cost factor at *l* to produce *m* from *k* ($PRODCL_{k,l,m}$) in \$ per tonne (Kozlowski, 2015)

Feedstock (*k*)	**Process (*l*)**	**Product (*m*)**	**Production cost factor (\$ per tonne of product)**
By-product	Briquetting	Briquette	65.00
Torrefied Pellet	Combustion 2	Steam2	20.70
Torrefied Pellet	Combustion 2	Ash2	0.00
Torrefied Pellet	Gasification	Syngas	240.00

Table 3.17 Approximated production cost factor at *n* to produce *o* from *m* ($PRODCN_{m,n,o}$) in \$ per tonne or per kWh (Kozlowski, 2015)

Feedstock (*m*)	**Process (*n*)**	**Product (*o*)**	**Production cost factor (\$ per tonne or \$ per kWh of product)**
Briquette	Combustion 1	Steam1	20.70
Briquette	Combustion 1	Ash1	0.00
Steam2	Power Generation 2	Electricity 2	0.132
Syngas	Catalytic Bioethanol Production	Bioethanol	150.00

Table 3.18 Approximated production cost factor at *r* to produce *u* from *o* ($PRODCR_{o,r,u}$) in \$ per kWh (Kozlowski, 2015)

Feedstock (*o*)	**Process (*r*)**	**Product (*u*)**	**Production cost factor (\$ per kWh of product)**
Steam1	Power Generation 1	Electricity 1	0.132

Table 3.19 Approximated conversion factor at *h* to produce *i* ($CONVH_{h,i}$) (Kozlowski, 2015)

Feedstock (*g*)	**Process (*h*)**	**Product (*i*)**	**Conversion factor**
Biomass (a,b, or c)	Animal Bedding	Animal Bed	0.80
Biomass (a,b, or c)	Blending Process	Blended Biomass 1 or 2	0.90
Biomass (a,b, or c)	Blending Process	Agricultural Mulch	0.10

Table 3.20 Approximated conversion factor at *j* to produce *k* from *i* ($CONVJ_{i,j,k}$) (Kozlowski, 2015)

Feedstock (*i*)	**Process (*j*)**	**Product (*k*)**	**Conversion factor**
Biomass 1	Milling & Sieving	Bio-filler	0.20
Biomass 1	Milling & Sieving	By-product	0.80
Biomass 2	Torrefied Pelletization	Torrefied Pellet	0.38

Table 3.21 Approximated conversion factor at *l* to produce *m* from *k* ($CONVL_{k,l,m}$) (Kozlowski, 2015)

Feedstock (*k*)	**Process (*l*)**	**Product (*m*)**	**Conversion factor**
By-product	Briquetting	Briquette	0.38
Torrefied Pellet	Combustion 2	Steam2	0.60
Torrefied Pellet	Combustion 2	Ash2	0.40
Torrefied Pellet	Gasification	Syngas	0.70

Table 3.22 Approximated conversion factor at *n* to produce *o* from *m* ($CONVN_{m,n,o}$) (Eurochlor, 2015)

Feedstock (*m*)	**Process (*n*)**	**Product (*o*)**	**Conversion factor**
Briquette	Combustion 1	Steam1	0.60
Briquette	Combustion 1	Ash1	0.40
Steam2	Power Generation 2	Electricity 2	250 kWh/tonne of steam
Syngas	Catalytic Bioethanol Production	Bioethanol	0.73

Table 3.23 Approximated conversion factor at *r* to produce *u* from *o* ($CONVR_{o,r,u}$) (Eurochlor, 2015)

Feedstock (*o*)	**Process (*r*)**	**Product (*u*)**	**Conversion factor**
Steam1	Power Generation 1	Electricity 1	250 kWh/tonne of steam

Table 3.24 Approximated biomass received cost ($/tonne) and availability (tonne/year) (Kozlowski, 2015)

Biomass	**Cost ($/tonne)**	**Availability (tonne/year)**
Biomass a	40	30000
Biomass b	45	50000
Biomass c	50	100000

Table 3.25 Approximated selling price of products ($/tonne or $/kWh) (Kozlowski, 2015 and O'Malley, 2013)

Product	**Selling Price ($/tonne or $/kWh)**
Animal Bed	154.32
Agricultural Mulch	75.00
Bio-filler	1102.30
By-product	65.00
Torrefied Pellet	156.00
Briquette	130.00
Ash 1	0.05
Ash 2	0.05
Electricity 1	0.263
Electricity 2	0.263
Bioethanol	950.00

Table 3.26 Approximated demands for products in tonne or kWh per year (Kozlowski, 2015)

Product	Demand in tonne or kWh per year
Animal Bed	70
Agricultural Mulch	75
Bio-filler	50
By-product	50
Torrefied Pellet	70
Briquette	30
Ash 1	40
Ash 2	40
Electricity 1	10000
Electricity 2	10000
Bioethanol	36

Conversion factors as shown by Table 3.19 till 3.23 represent efficiencies of processing units such as reactor or blending machine to convert inlet feeds into bio-products. At the same stage of processing facility, for example at the blending process, incoming biomass feedstocks were converting into blended biomasses and the residues i.e the agricultural mulch by 0.9 and 0.1 of conversion factors, respectively. These conversion factors were considered by mass ratio of inlet to the outlet. However, for the cases where incoming feeds are steam (steam1 and steam2) to produce electricity (electricity 1 and electricity 2), conversion factors have approximated the turbine's efficiencies on how much power would be produced per mass of steam which depends on pressure and temperature of inlet and outlet steam.

3.5 Results and Discussions

In searching for optimal value, optimization software i.e GAMS Rev 149 with CPLEX 11.0.0 solver has been used. The CPLEX optimizer is designed to solve large and difficult optimization problems quickly and with minimal user's intervention (GAMS, 2015). The developed CPLEX algorithm in GAMS could solve problems related to linear, quadratically constrained and mixed integer programs. The solution was performed in AMD A10-4600M APU processor, contained 27 blocks of equations, 22 blocks of variables, 274 single equations, 366 single variables and took 0.137 seconds to solve. For the given parameters, the optimal profit was found to be $ 22,618,673 per year that counted for all of the products. The optimized production level for each bio-product and individual contribution to the profit are shown in Table 3.27, and ranked according to the most profitable one. For this to happen, all of Biomass a, Biomass b, and Biomass c have been utilized at their maximum availabilities which are 30000, 50000, and 100000 tonnes per year, respectively.

Beside bio-filler, it is sensible for the company at this moment to start manufacturing bio-ethanol and agricultural mulch, as well as to look for other profitable applications for their by-product from milling and sieving plant. Unless market situations would have changed, it is not necessary for them to produce other bio-products (torrefied pellet, animal bed, briquette, electricity, and ash). They were also could produce nutrients from the biomass (as shown in the superstructure) if the demands are high enough to justify economic viability.

In addition, the developed model has considered Omtec Inc. as the single owner for all of the facilities in the supply chain. It also would be in the case of Omtec Inc. as the main consultant for this project that facilitates other interested companies for their investments. It is important to highlight that the results are based on the estimated values of all involved parameters and hence might need to be refined for future uses. However, the current developed model is adequate to serve as a simulation or what-if-scenario tool for Omtec for their benefits. Since the current model only emphasizes economic efficiency of the supply chain, other criteria such as environmental impacts, technological investment risks and health and safety issues could be added in the future.

Table 3.27 Optimal production level for bio-products and their calculated contributions to the annual profit

Produced Products	Optimal Production Level (tonne per year or kWh per year)	Profit Contribution ($/year)	Profit Contribution (%)
Bio-filler	32384.25	10,727,735.77	47.429
Bio-ethanol	31355.00	8,951,685.74	39.577
By-product	129194.90	2,523,673.36	11.157
Agricultural Mulch	17991.25	405,505.75	1.793
Torrefied Pellet	70.00	3281.69	0.015
Animal Bed	70.00	3246.34	0.014
Briquette	30.00	1172.03	0.005
Electricity 1	15000.00	1185.55	0.005
Electricity 2	15000.00	1185.55	0.005
Ash1	40.00	0.60	Negligible
Ash2	40.00	0.60	Negligible
Total		**22,618,673**	**100.00**

Optimal production levels for some bio-products have exceeded the local demands as these might let the company to export them to the nearby regions. Table 3.28 till Table 36 show other optimization results from GAMS for optimal decision variables in tonnes or kWh per year.

Table 3.28 Optimal amounts of biomass source, *g* transported to pre-processing facilities *h* in tonne per year

$(FTRPF_{g,h})$

Origin	Destination	Amount
Biomass a	Blending	29912.500
Biomass a	Animal bedding	87.500
Biomass b	Blending process	50000.000
Biomass c	Blending process	100000.000

Table 3.29 Optimal amounts at pre-processing facilities, *h* in tonne per year

Pre-processing facility	Pre-processed product/by-product	Produced amount $(\boldsymbol{FPRDH_{h,i}})$	Amount to be sold directly $(\boldsymbol{FTRSH_{h,i}})$
Blending process	Blended biomass 1	161921.250	-
Blending process	Blended biomass 1	161921.250	-
Blending process	Agriculture mulch	17991.250	17991.250
Animal bedding	Animal bed	70.000	70.000

Table 3.30 Optimal amounts of pre-processed products *i* transported from pre-processing facilities *h* to processing one facilities *j* in tonne per year

$(FTRPH_{h,i,j})$

Origin	Destination	Amount
Blended biomass 1 from blending process	Milling & sieving	161921.250
Blended biomass 2 from blending process	Torrefied pelletization	161921.250

Table 3.31 Optimal amounts at processing one facilities, *j* in tonne per year

Processing one facility	Processed one product	Produced amount $(\boldsymbol{FPRDJ_{i,j,k}})$	Amount to be sold directly $(\boldsymbol{FTRSJ_{j,k}})$
Milling & sieving	Bio-filler	32384.250	32384.250
Milling & sieving	By-product	129537.000	129194.895
Torrefied pelletization	Torrefied pellet	61530.075	70.000

Table 3.32 Optimal amounts of processed one product *k* transported from processing one facilities *j* to processing two facilities, *l* in tonne per year

$(FTRPJ_{j,k,l})$

Origin	Destination	Amount
By product from milling & sieving	Briquetting	342.105
Torrefied pellet from torrefied pelletization	Combustion2	100.000
Torrefied pellet from torrefied pelletization	Gasification	61360.075

Table 3.33 Optimal amounts at processing two facilities, *l* in tonne per year

Processing two facility	Processed two product	Produced amount $(\boldsymbol{FPRDL_{k,l,m}})$	Amount to be sold directly $(\boldsymbol{FTRSL_{l,m}})$
Briquetting	Briquette	130.000	30.000
Combustion2	Steam2	60.000	-
Combustion2	Ash2	40.000	40.000
Gasification	Syngas	42952.052	-

Table 3.34 Optimal amounts of processed two product, *m* transported from processing two facilities, *l* to processing three facilities, *n* in tonne per year

$(FTRPL_{l,m,n})$

Origin	Destination	Amount
Briquette from briquetting	Combustion1	100.000
Steam2 from combustion2	Power generation 2	60.000
Syngas from gasification	Catalytic bioethanol production	42952.052

Table 3.35 Optimal amounts at processing three facilities, *n* in tonne/kWh per year

Processing three facility	Processed three product	Produced amount $(\boldsymbol{FPRDN_{m,n,o}})$	Amount to be sold directly $(\boldsymbol{FTRSN_{n,o}})$
Combustion1	Steam1	60.000	-
Combustion1	Ash1	40.000	40.000
Power generation 2	Electricity 2	15000.000	15000.000
Catalytic bioethanol production	Bioethanol	31354.998	31354.998

Table 3.36 Optimal amounts of processed three products transported from processing three facilities, n to processing four facility, r in tonne per year

$(FTRPN_{n,o,r})$

Origin	Destination	Amount
Steam1 from combustion1	Power generation 1	60.000

Table 3.37 Optimal amounts at processing four facility, r in kWh per year

Processing four facility	Final product	Produced amount $(\boldsymbol{FPRDR_{o,r,u}})$	Amount to be sold $(\boldsymbol{FTRSR_{r,u}})$
Power generation 1	Electricity 1	15000.000	15000.000

Furthermore, in order to view direct influences of approximated parameters with the optimal value, sensitivity analysis was performed. Basically, this analysis would answer to the question for what rate does the objective function value should change with perturbations from one parameter or some of parameters. As for this chapter, biomass costs were varied in order to the record changes in the profit's values, shown by Figure 3.4.

From the figure, increments in biomass resources costs have a direct impact to the profit with linear pattern. This is important relationship especially for Biomass c since this type of biomass has been utilized with the largest quantity as compared to Biomass b and Biomass a. All of the factors that are associated with the biomass resources cost such as seasonal, competing uses, and so on, should be monitored closely due to this pattern.

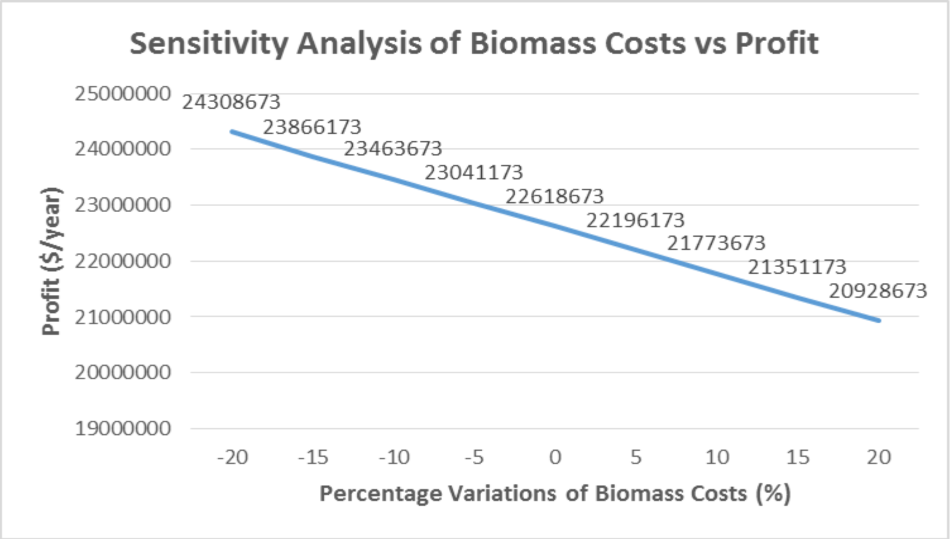

Figure 3.4 Sensitivity analysis for effect of biomass cost towards profit

3.6 Conclusion and Future Works

In conclusion, the developed model has provided and considered options that exist in the supply chain such as to produce different kind of products that are categorized as energy, chemicals or materials from multiple biomass resources. Furthermore, depending to the market situations, the company may prioritizes product lines and the necessity to further process a product once it has been produced. We believe these have helped the company in having greater flexibilities in their planning and operation. Even though it was modeled and optimized specifically for the company in Ontario, Canada, the general framework of the optimization model is however could be applicable and may be extended for other biomass utilization projects that involve supply chain.

Since the current model only emphasizes economic efficiency of the supply chain, other criteria such as environmental impacts, technological investment risks and health and safety issues could be added in the future works as to represent more comprehensive efforts for achieving sustainability. For the pre-determined transportation mode, the current model has yet to consider optimal selection of the mode by including integer variables. This inclusion would provide better assignments of transportation modes depending to the distance, product density and other economic factors. Up to this point, the approximated parameters that were used in executing the model were considered adequate to demonstrate the model's practicality in solving the optimization problem. However, more refinements of the parameters are necessary once the real operation data are available.

Chapter 4

Multi-products Productions from Malaysian Oil Palm Empty Fruit Bunch (EFB): Analyzing Economic Potentials from Optimal Supply Chain

4.1 Abstract

The economic potentials of Malaysian oil palm EFB are realized by several motivating factors such as abundance, cheapness and are generally feasible to produce multi-products that range from energy, chemicals and materials. Amid continuing supports from the government in terms of policies, strategies and funding, manufacturing planning to utilize this biomass resource requires a fundamental tool for the decision making process. Biomass supply chain model in this context can present economic analysis in order to guide future investments. Sequential steps in modeling and optimization of EFB's supply chain were explained. In a form of superstructure, the supply chain consisted processing stages for converting EFB into intermediates and products, transportation networks, and options for product's direct sale or for further refinements. Economic analysis have considered biomass cost, production costs, transportation costs, and emission treatment costs from transportation and production in calculating the profit. In the case of Peninsula Malaysia, optimal value showed a profit of $ 713,642,269 per year could be achieved by a single ownership for all of the facilities in the supply chain. The conclusions were drawn based on the limitation, availability and quality of parameters or data used in this study.

4.2 Introduction

Malaysia is a nation that is endowed with resources of both fossil as well as renewables. For fossil resources, proved reserves and the global share (%) for this country are 3.7 million barrel and 0.2% for oil, and 38.5 trillion cubic feet and 0.6% for natural gas (BP, 2014). These numbers have ranked Malaysia as the 28th and the 15th largest reserves in the world for oil and natural gas, respectively. For renewables, Malaysia has 22500 MW energy potential of hydropower, 6500 MW energy potential of solar, and 1700 MW energy potential of biomass (Mekhilef et al., 2011). Of these renewables, only biomass can be used as a substituted feedstock to the fossil fuels for the manufacturing of multi-products that ranged from energy, chemicals and materials. The substitutions to a certain extent are apparent due to the fact that there were declines in productions of Malaysia's major oil fields and there are abundances of biomass resources available in this country (EIA, 2015; Zafar, 2014). On the more general motivations, discouraged attributes of fossil resources such as environmentally harmful and are not renewable have even elevated the prospects of biomass to become the main renewable feedstocks in the near future.

In Malaysia, biomass resources are mainly generated by the palm oil industry. The crop's planted areas have reached five million hectares in which almost 93 million tonnes of oil palm fruit was harvested (Ng and Ng, 2013). This harvested oil palm fruit will then produce crude palm oil and crude palm kernel oil, the major raw materials for the productions of various basic oleochemicals and biodiesel (Rupilius and Ahmad, 2007). Despite producing valuable products, the palm oil industry also generates agricultural wastes (biomass) such as palm oil fronds, palm oil trunks, empty fruit bunch (EFB), palm oil mill effluent (POME), palm mesocarp fiber (PMF), and palm kernel shell (PKS). In the case of EFB, for every 1 tonne of oil palm fresh fruit bunch processed, it was estimated that 230 kg of EFBs would be generated (Ng and Ng, 2013). As cheap biomass resource, EFB could be important feedstock to produce various products. This move is indeed in line with the current government strategies such as the Renewable Energy Policy, the National Biomass Strategy 2020 and the 1 Malaysia Biomass Alternative Strategy, which encourages biomass utilization for value-added product production and bioenergy generation (Ng and Ng, 2013).

Previous research and commercialization activities have indicated that EFB has been subjected to produce numerous products such as bio-syngas, bio-oil, bio-hydrogen, briquette and pellet fuels, bio-ethanol, bio-composite, bio-resin, bio-gas, bio-compost, activated carbon, xylose, polyhdroxybutyrate, and etcetera (Lahijani and Zainal, 2010; Salema and Ani, 2012; Md. Zin et al., 2012; Chong et al., 2013; Tan et al., 2010; Tan et al., 2012; Tay et al., 2009; Ibrahim et al., 2011; Purwandari et al., 2012; Rosli et al., 2011; Foo and Hameed, 2011; Auta et al., 2012, Zhang et al., 2013, and Rahman et al., 2007). Some of these are intermediates that will be further refined to produce final products. Table 4.1 shows huge potentials of products and their applications which are feasibly derived from EFB.

Table 4.1 Applications for products from oil palm EFB

Bio-products	Applications
Dry Long Fiber (DLF)	Mattress and cushion production, ceramic and brick production, and pulp and paper production.
Bio-compost	Organic farming, soil conditioner and fertilizer in gardens, landscaping, horticulture, agriculture as well as it can be used as erosion control.
Activated carbon	Adsorbent for purifications in water treatment, air pollution, gas processing, odor and color removals.

Cellulose	Productions of derivatives from methyl cellulose such as carboxymethyl cellulose (CMC), hydroxyethyl cellulose (HEC), acetate, nitrocellulose, nanofibrillated cellulose (NFC), nanocrystalline cellulose (NCC), and cellulose filaments.
Hemicellulose	Productions of xylitol, ethanol and organic acids (from xylose) and lubricants, coatings, adhesives, resins, nylon-6, and nylon-6,6 (from furfural).
Lignin	Bio-resins (polymer substitution) in phenolic resins and polyurethane foams, carbon fiber composite, glue, dispersants, binder for fuel pellet, and combustion fuel.
Briquette	Thermal applications such as steam generation in boilers, power production, space heating, drying, and cooking.
Pellet	Thermal applications such as steam generation in boilers, power production, space heating, drying, and cooking.
Torrefied Pellet	Thermal applications such as steam generation in boilers, power production, space heating, drying, and cooking.
Bio-composite	Building products productions such as windows, doors, patio furniture, fencing, decking, roofing, and railing. Automotive applications such as dashboard, floor mats, seat fabric, and etc.
Carboxymethyl Cellulose (CMC)	Thickener in the ice cream, canned food, fast cooking food, jam, syrup, sherbet, dessert, drinks, etc. Emulsifying, suspending, fixing, smoothing, and separating agent, dirt absorbent in synthetic detergent, as well as used in the oil and gas drilling process.
Glucose	Simple sugar for fermentation, anaerobic digestion and isomerization.
Xylose	Simple sugar for xylitol production as well as for fermentation and anaerobic digestion processes.
Bio-resin	Compostable and biodegradable plastics such thermoplastic starch (TPS), polyhydroxyalkanoates (PHA) and polyactide (PLA).
High Pressure Steam	Mainly for power generation.
Bio-syngas	Productions of ammonia, hydrogen, methanol, electricity and range of transportation fuels through Fischer-Tropsch process.
Bio-oil	Productions of bio-hydrogen, bio-ethylene, bio-propylene, transportation fuels through refining process, glycolaldehyde, levoglucosan, and etc.
Bio-char	Soil enhancer, carbon sequester, fuels, and metal extraction where carbon is used to remove oxide from metal.
Bio-hydrogen	Ammonia production, refinery applications in hydrotreating and hydrocracking processes, fuel cells, and etc.
Xylitol	Various pharmaceutical and oral hygiene products.
Bio-ethanol/ethanol	Blending with gasoline, and uses commonly in the sectors such as beverages, cosmetics, medical and pharmaceuticals.
Bio-gas	Power generation, heating, combined heat and power, drying, cooling, cooking, compressed liquid fuel for transportation and etc.

Bio-methanol	Formaldehyde production, wastewater denitrification, solvent for biodiesel trans-esterification, and other materials and chemicals productions such as paints, solvents, adhesives, refrigerants, synthetic fibers, and etc.
Electricity	Energy for electrical devices such as pump, compressor, fan, air-conditioner, heater, lighting system, computers, and many more.
Medium Pressure Steam	Power production, heating, cleaning, as reaction medium, humidification, and etc.
Low Pressure Steam	Heating, cleaning, humidification, moisturizing agent, and etc.
Bio-ethylene	Productions of polyethylene (PE), ethanol, ethylene glycol, ethylene oxide, ethylbenzene, ethylene dichloride, fruit ripening agent, and etc.
Bio-diesel	Transportation fuel, steam and power productions for diesel engines.
Bio-gasoline	Main transportation fuel in for road vehicles, motorboats, as well as for chainsaws, lawn movers, and etc.
Ammonia	Mainly used for the productions of fertilizers, plastics such as polyurethane, refrigerant, and etc.
Formaldehyde	Productions of formaldehyde-based resins or adhesives such as urea formaldehyde (UF) resins, phenol formaldehyde (PF) resins, and melamine formaldehyde (MF) resins, polyoxymethylenes (POM), healthcare applications such as disinfectants and vaccines, and etc.

One of the main factors to realize these potentials is by having an optimal supply chain. The supply chain will ensure conversion routes that comprise series of pre-processing, main processing, and further processing steps to produce those above-mentioned products are considered simultaneously and comprehensively. Previous studies that focused on EFB's supply chains including the supply chain analysis and life cycle assessment for the productions of green chemicals (Reeb et al., 2014) the supply chain of EFB for renewable fuel production (Eco-Ideal Consulting Sdn. Bhd. and Mensilin Holdings Sdn. Bhd., 2005), and the synthesis of energy supply chain from EFB (Lam et al., 2010). Optimal EFB's supply chain for multi-products productions of energy, chemicals and materials is yet to be studied based on author's knowledge. Therefore, this chapter will focus on modeling an optimization of EFB's supply chain by taking Peninsular Malaysia as a case study.

4.3 Model Development for Optimal EFB's Supply Chain

An optimization model of the EFB's supply chain has been developed according to the sequential steps shown in Figure 4.1. As lignocellulosic biomass sources, EFB will take different processing routes, each will end up to produce the pre-determined bio-products as highlighted in Table 4.1. These processing routes comprise stages of pre-processing, main processing and further processing steps. The routes can generally be divided into three main categories; thermochemical, chemical and biochemical processes.

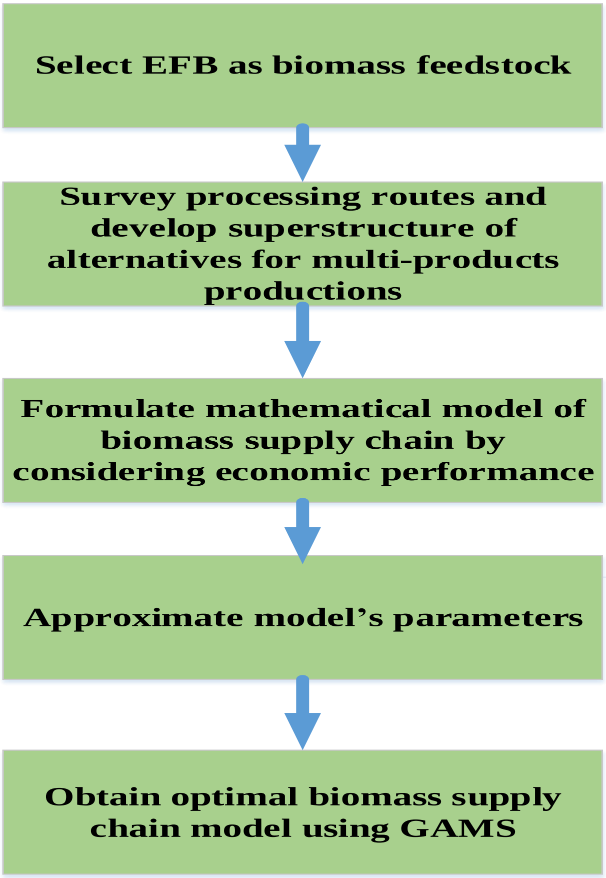

Figure 4.1 Sequential steps for optimal EFB's supply chain

In developing the supply chain's superstructure, important steps and approaches, as detailed out by Murillo-Alvarado et al., (2013) were considered. First, suitable biomass feedstocks are recognized and followed by identification of desired products. In this step, several desired products can be generated by consuming the same feedstocks through a variety of conversion routes. Meanwhile, more than one reactants can be used to produce the desired product. In order to identify the interconnections (processing pathways) between feedstocks and products, two approaches are used which the forward synthesis of biomass and the backward synthesis of desired products. The next step is to match two intermediate compounds obtained from forward and backward syntheses. The final step of superstructure generation involved interception of the two intermediate compounds by identifying the set of processing technologies required for connecting these compounds. The developed superstructure is shown in Figure 4.2. In this superstructure, square shapes represent processing facilities while oval shapes depict storages. Each storage was assumed to be located within its facility. The solid lines show processing sequences while the dash lines provide options to sell the products directly. Portions of the products whether to be sold directly or to be transferred to the next processing step would be determined from optimization results. There was assumption that the EFB feedstocks were blended homogenously. Furthermore, competitive utilizations could be seen for EFB, cellulose, hemicellulose, pellet, torrefied pellet, glucose, xylose, bio-syngas, and bio-oil. Small letters of *g* to *o* are subscripts and are explained in Table 4.2. The subscript *p* is not shown in Figure 4.2 but will be used in the mathematical model. This subscript *p* represents sum up of products.

Table 4.2 List of subscript and description in Figure 4.2

Set/Subscripts	Descriptions	Contents
g	Biomass source storage locations	EFB collection 1, EFB collection 2, and EFB collection 3.
h	Pre-processing facilities	DLF production, aerobic digestion, alkaline activation, extraction, briquetting, palletization, and torrefied palletization.
i	Pre-processed feedstocks storages	PEFB DLF, bio-compost, activated carbon, cellulose, hemicellulose, lignin, PEFB briquette, PEFB pellet, and PEFB torrefied pellet.
j	Main processing facilities	Bio-composite production, CMC production, acid hydrolysis, enzymatic hydrolysis, resin production, boiler combustion, gasification, fast pyrolysis, and slow pyrolysis.
k	Intermediate products 1 storages	Bio-composite, CMC, glucose, xylose, bio-resin, HP steam, bio-syngas, bio-oil, and bio-char.
l	Further processing 1 facilities	Steam reforming, separation, xylitol production, fermentation, anaerobic digestion, power production, methanol production, bio-oil upgrading, and FTL productions.
m	Intermediate products 2 storages	Bio-hydrogen, bio-methanol, xylitol, bio-gas, electricity, MP steam, LP steam, bio-gasoline, bio-diesel, and bio-ethanol.
n	Further processing 2 facilities	Ammonia production, formaldehyde production, bio-ethylene production.
o	Final products storages	Ammonia, formaldehyde, and bio-ethylene
p	Sum of products	PEFB DLF, bio-compost, activated carbon, cellulose, hemicellulose, lignin, PEFB briquette, PEFB pellet, PEFB torrefied pellet, Bio-composite, CMC, glucose, xylose, bio-resin, HP steam, bio-syngas, bio-oil, bio-char, Bio-hydrogen, bio-methanol, xylitol, bio-gas, electricity, MP steam, LP steam, bio-gasoline, bio-diesel, bio-ethanol, ammonia, formaldehyde, and bio-ethylene.

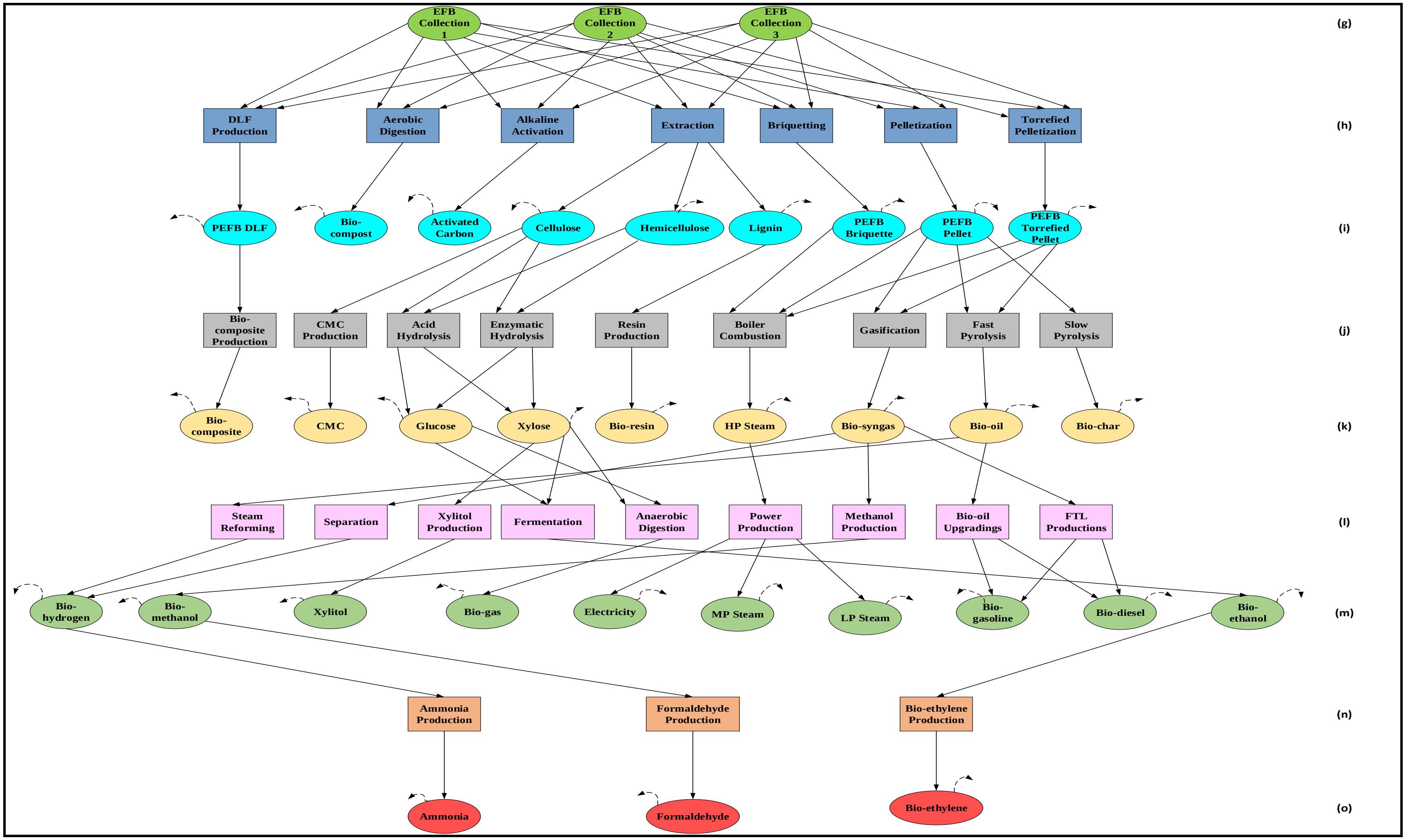

Figure 4.2 A superstructure of supply chain for multi-products productions from EFB

Next, mathematical model of the optimal supply chain would be developed by considering economic performance. This refers to the profitability from the selling of products minus all the associated costs. Hence, the objective function of the optimization model is to maximize the overall profit, i.e,

- Maximize Profit = Revenues – Costs, where;
- Revenues = (Sales of products), and
- Costs = (Biomass cost + Transportation cost + Production cost + Emission cost from transportation + Emission cost from production).

Therefore, Profit = (Sales of products) - (Biomass cost) - (Transportation cost) - (Production cost) - (Emission cost from transportation) - (Emission cost from production).

Each of the term above requires data or parameters which among them are transportation cost factors, production cost factors, carbon dioxide (CO_2) emission factors from transportation, CO_2 emission factors from production and conversion factors. The transportation cost factors were calculated using method from Oo et al., (2012) and Blok et al., (1995). Transportation modes such as truck and train have constants for variable cost and fixed cost. The variable cost include the operating cost, while the fixed cost include the capital cost. The transportation cost factors will be in $ per tonne and later will be multiplied with mass flowrate in order to determine the transportation cost. In this chapter, truck would be pre-selected for distances up to 100 km, while train was chosen for distances beyond 100 km for solid transportation. For liquid and gaseous products, pipeline transportation would be used. Production cost factor was the cost in $ to produce one unit capacity of product. In this regard, Mani et al. (2006) have reported that this cost factor comprised capital and operating costs for the equipment. CO_2 emission cost factors from transportation were determined from the model that was developed by McKinnon (2008). Depending on the pre-selected mode of transportation, these emission factors would be then multiplied with mass flowrate in the supply chain. The CO_2 emission factors from production meanwhile were taken from various life cycle analysis and relevant literatures. Unit for both emission factors was reported as CO_2 equivalent as this is the standard international unit of measurement for expressing all greenhouse emissions in terms of the global warming potential of CO_2. The cost for emission treatment was fixed at $40 per tonne of CO_2 equivalent, but in practice the cost much depends on the local’s regulation. Conversion factors were defined by mass ratio of inlet to the outlet for each processing facility. However, for power production, conversion factors have approximated the turbine's efficiencies on how much electricity would be produced per mass of inlet steam which depends on pressure and temperature of inlet and outlet steam.

Tables 4.3 till 4.21 tabulate all the required parameters for the mathematical model. It is worth to mention that, one of the efforts in this study was to collect and record all of these parameters. Since the majority of the biomass utilizations involving EFB are currently still in the conceptual stage, approximations were used. Hence, the parameters were assumed to be independent of scale, input types and conditions. This assumption does not restrict the validity of the optimization model that will be presented in a general form.

Table 4.3 Products' selling prices derived from EFB

Product	**Selling price ($/tonne or $/MWh)**	**Reference**
Dry Long Fiber (DLF)	210	Ng and Ng (2013)
Bio-compost	100	Ng and Ng (2013)
Activated carbon	1756	Shanghai Jinhu Inc. (2014)
Cellulose	2200	Higson (2011)
Hemicellulose	2000	Assumed value based on cellulose and lignin prices
Lignin	1500	Lake (2010)
Briquette	120	Ng and Ng (2013)
Pellet	140	Ng and Ng (2013)
Torrefied Pellet	160	Assumed value based on PEFB pellet and PEFB briquette
Bio-composite	625	ERIA (2014)
Carboxymethyl Cellulose (CMC)	3500	www.trade.ec.europa.eu
Glucose	1890	www.cascadebiochem.com
Xylose	1990	www.cascadebiochem.com
Bio-resin	9072	www.bioresins.eu
High Pressure Steam	26	Ng and Ng (2013)
Bio-syngas	600	IChemE (2014)
Bio-oil	800	Careddi Technology Ltd. (2014)
Bio-char	380	Ng and Ng (2013)
Bio-hydrogen	818	Murillo-Alvarado et al., (2013)
Xylitol	4200	Shanghai Yanda Biotechnology Ltd. (2014)
Bio-ethanol	523	Murillo-Alvarado et al. (2013)
Bio-gas	398	Oo et al. (2012)
Bio-methanol	870	Murillo-Alvarado et al. (2013)
Electricity	140	Ng and Ng (2013)
Medium Pressure Steam	17	Ng and Ng (2013)
Low Pressure Steam	12	Ng and Ng (2013)
Bio-ethylene	1544	ICIS (2014)
Bio-diesel	790	Murillo-Alvarado et al. (2013)
Bio-gasoline	1315	EIA (2014)
Ammonia	745	ICIS (2014)
Formaldehyde	463	ICIS (2014)

Table 4.4 Annual demands for products in tonne/year

Product	World demands (Tonne/year) or (MWh/year)	Product demands (Tonne/year) or (MWh/year)	Reference
Dry Long Fiber	85.4 x 10^6	85.4	Lenzing Group AG (2014)
Bio-compost	0.4 x 10^6	0.4	Biocomp Nepal (2014)
Activated carbon	1.9 x 10^6	1.9	www.filtsep.com
Cellulose	5.81 x 10^6	5.81	Lenzing Group AG (2014)
Hemicellulose	15 x 10^6	15	Christopher (2012)
Lignin	0.6 x 10^6	0.6	International Lignin Institute (2014)
Briquette	30 x10^6	30	Assumed value based on pellet and torrefied pellet demands
Pellet	37 x 10^6	37	O'Carroll (2012)
Torrefied Pellet	70 x 10^6	70	www.biomassmagazine.com
Bio-composite	0.92 x10^6	0.92	Carus (2012)
Carboxymethyl Cellulose (CMC)	0.4 x10^6	0.4	www.prweb.com
Glucose	5.81 x 10^6	5.81	Assumed value based on cellulose demand
Xylose	15 x 10^6	15	Assumed value based on hemicellulose demand
Bio-resin	0.2 x 10^6	0.2	www.thomasnet.com
High pressure steam	2.0 x10^6	2	www.enerdata.com
Bio-syngas	462000 x 10^6	462000	Boerrigter and Drift (2005)
Bio-oil	5 x 10^6	5	Bradley (2006)
Bio-char	3000 x10^6	3000	www.nature.com
Bio-hydrogen	375.5 x 10^6	375.5	Santibanez-Aquilar et al. (2011)
Xylitol	0.002 x 10^6	0.002	www.companiesandmarket.com
Bio-ethanol	3.6 x 10^6	3.6	Santibanez-Aquilar et al. (2011)
Bio-gas	9 x10^6	9	Svensson (2010)
Bio-methanol	0.3 x 10^6	0.3	Murillo-Alvarado et al. (2013)
Electricity	20 x 10^6 MWh	20	www.enerdata.com
Medium pressure steam	0.9 x10^6	0.9	Assumed value for 50% of high pressure steam
Low pressure steam	0.45 x 10^6	0.45	Assumed value for 50% of medium pressure steam
Bio-ethylene	140 x10^6	140	Technip (2014)
Bio-diesel	0.8 x10^6	0.8	Santibanez-Aquilar et al. (2011)
Bio-gasoline	1.2 x10^6	1.2	EIA (2014)
Ammonia	170.0 x 10^6	170	www.hazmatmag.com
Formaldehyde	42 x 10^6	42	Lubon Industry Ltd. (2013)

Malaysia is geographically separated by two regions by the South China Sea. These two regions are called as Peninsula Malaysia and East of Malaysia. In the Peninsula as shown in Figure 4.3, the main areas of palm oil plantations, and hence the main areas of EFB producers are situated in states of

Johore, Pahang, and Perak (MPOB, 2013). Hence, in this study, only these three states were considered for EFB collection points as shown by Table 4.5. Locations of the processing facilities (pre-processing, main processing, further processing 1, and further processing 2) were considered for the Peninsula Malaysia. Operational status of these processing facilities are either fully operational, nearly operation or at a demonstration level. Distances for connecting two processing facilities were determined using Google Maps. In addition, biomass cost of the EFB was $6 per tonne.

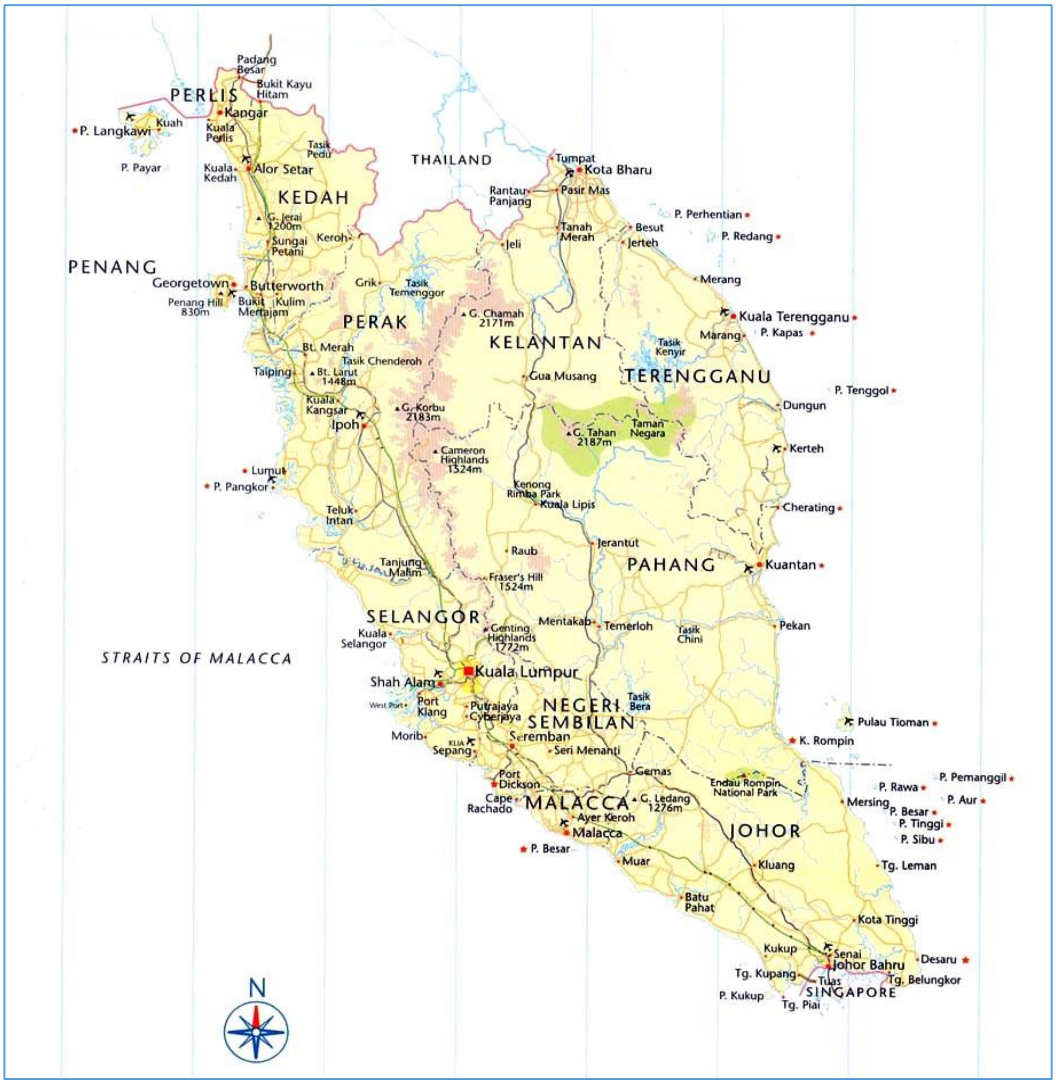

Figure 4.3 Map of Peninsula Malaysia

Table 4.5 Biomass feedstock availability for Johore, Pahang and Perak

Biomass feedstock	Fresh fruit bunch yield (Tonne/hectare)	Plantation area (Hectare)	Fresh fruit bunch production (Tonne)	Palm empty fruit bunch productions (Tonne)*	Reference
EFB Collection 1 (Johore)	19.49	730694	14241226.06	3275481.99	MPOB (2014)
EFB Collection 2 (Pahang)	20.21	710195	14353040.95	3301199.42	
EFB Collection 3 (Perak)	20.31	384594	7811104.14	1796553.95	
Total	60.01	1825483	36405371.15	8373235.36	

* 23% of fresh fruit bunch will be assumedly to produce EFB as reported by Ng and Ng (2013)

Table 4.6 Approximated transportation cost and CO_2 emission factor for EFB feedstock from *g* to *h*

EFB storage, *g*	Pre-processing facility, *h*	Distance (km)	Transportation mode	Cost ($/tonne)	CO_2 emission factor (tonne CO_2 equivalent /tonne of biomass transported)
EFB Collection 1	Aerobic Digestion	0	-	0	0
EFB Collection 1	DLF Production	271	Train	29.54	0.0060
EFB Collection 1	Extraction Plant	322	Train	31.24	0.0071
EFB Collection 1	Briquetting Plant	271	Train	29.54	0.0060
EFB Collection 1	Pelletization Mill	287	Train	29.98	0.0063
EFB Collection 1	Torrefied Pelletization	208	Train	27.45	0.0046
EFB Collection 1	Alkaline Activation (Activated Carbon) Plant	208	Train	27.45	0.0046
EFB Collection 2	Aerobic Digestion	0	-	0	0
EFB Collection 2	DLF Production	165	Train	26.01	0.0036
EFB Collection 2	Extraction Plant	230	Train	28.18	0.0051
EFB Collection 2	Briquetting Plant	165	Train	26.01	0.0036
EFB Collection 2	Pelletization Mill	195	Train	27.01	0.0043
EFB Collection 2	Torrefied Pelletization Mill	224	Train	27.98	0.0049
EFB Collection 2	Alkaline Activation (Activated Carbon) Plant	224	Train	27.98	0.0049
EFB Collection 3	Aerobic Digestion	0	-	0	0
EFB Collection 3	DLF Production	274	Train	29.64	0.0060

EFB Collection 3	Extraction Plant	486	Train	36.70	0.0107
EFB Collection 3	Briquetting Plant	274	Train	29.64	0.0060
EFB Collection 3	Pelletization Mill	289	Train	30.14	0.0064
EFB Collection 3	Torrefied Pelletization Mill	346	Train	32.04	0.0076
EFB Collection 3	Alkaline Activation (Activated Carbon) Plant	346	Train	32.04	0.0076

Table 4.7 Approximated transportation cost and CO_2 emission factor for pre-processed feedstock from *h* to *j*

Pre-processing facility, *h*	**Main processing facility, *j***	**Distance (km)**	**Transportation mode**	**Cost ($/tonne)**	**CO_2 emission factor (tonne CO_2 equivalent /tonne of product transported)**
Extraction Plant	CMC Production	0	-	0	0
Extraction Plant	Acid Hydrolysis	546	Train	38.70	0.0120
Extraction Plant	Enzymatic Hydrolysis	315	Train	31.00	0.0069
Extraction Plant	Resin Production	386	Train	33.37	0.0085
DLF Production	Bio-composite Production	33	Truck	12.26	0.0020
Briquetting Plant	Boiler Combustion	83	Truck	20.46	0.0051
Pelletization Mill	Boiler Combustion	88	Truck	21.28	0.0055
Pelletization Mill	Gasification	17	Truck	9.63	0.0011
Pelletization Mill	Fast Pyrolysis	0	-	0	0
Pelletization Mill	Slow Pyrolysis	345	Train	32.01	0.0076
Torrefied Pelletization Mill	Boiler Combustion	23	Truck	10.61	0.0014
Torrefied Pelletization Mill	Gasification	78	Truck	19.64	0.0048
Torrefied Pelletization Mill	Fast Pyrolysis	86	Truck	20.95	0.0053

Table 4.8 Approximated transportation cost and CO_2 emission factor for intermediate product 1, *k* from *j* to *l*

Main processing facility, *j*	**Further processing 1 facility, *l***	**Distance (km)**	**Transportation mode**	**Cost ($/tonne)**	**CO_2 emission factor (tonne CO_2 equivalent /tonne of product transported)**
Acid Hydrolysis	Fermentation Plant	327	Train	31.41	0.0072
Acid Hydrolysis	Anaerobic Digestion Plant	338	Train	31.78	0.0074
Acid Hydrolysis	Xylitol Production	0	-	0	0
Enzymatic Hydrolysis	Fermentation Plant	65	Truck	17.51	0.0040
Enzymatic Hydrolysis	Anaerobic Digestion Plant	37	Truck	12.91	0.0023

Enzymatic Hydrolysis	Xylitol Production	379	Train	33.14	0.0083
Boiler Combustion	Power Production	0	-	0	0
Gasification	Separation Plant	0	-	0	0
Gasification	Methanol Production	404	Pipeline	20.20	0
Gasification	FTL production	19	Pipeline	0.95	0
Fast Pyrolysis	Bio-oil Upgrading	94	Pipeline	4.70	0
Fast Pyrolysis	Steam Reforming Plant	0	-	0	0

Table 4.9 Approximated transportation cost and CO_2 emission factor for intermediate product 2, m from *l* to *n*

Further processing 1 facility, *l*	Further processing 2 facility, *n*	Distance (km)	Transportation mode	Cost ($/tonne)	CO_2 emission factor (tonne CO_2 equivalent /tonne of product transported)
Steam Reforming Plant	Ammonia Production	361	Pipeline	18.05	0
Separation Plant	Ammonia Production	367	Pipeline	18.35	0
Methanol Production	Formaldehyde Production	686	Pipeline	34.30	0
Fermentation Plant	Bio-ethylene	316	Pipeline	15.80	0

Table 4.10 Approximated production cost factor at *h* in $ per tonne

Biomass type, *g*	Pre-processing, *h*	Pre-processed product, *i*	$/tonne	Reference
Blended EFBs	DLF Production	Dry Long Fiber	85	www.hempfarm.com
Blended EFBs	Aerobic Digestion	Bio-compost	10	Fabian et al. (1993)
Blended EFBs	Alkaline Activation	Activated Carbon	144	Lima et al. (2008)
Blended EFBs	Extraction	Cellulose	125	Murillo-Alvarado et al. (2013)
Blended EFBs	Extraction	Hemicellulose	130	Murillo-Alvarado et al. (2013)
Blended EFBs	Extraction	Lignin	135	Murillo-Alvarado et al. (2013)
Blended EFBs	Briquetting	Briquette	50	Kanna (2010)
Blended EFBs	Pelletization	Pellet	60	PPD Technologies Inc. (2011)
Blended EFBs	Torrefied Pelletization	Torrefied Pellet	70	PPD Technologies Inc. (2011)

Table 4.11 Approximated conversion factor at *h*

Biomass type, *g*	Pre-Processing, *h*	Pre-processed product, *i*	Conversion factor	Reference
Blended EFBs	DLF Production	Dry Long Fiber	0.37	Ng and Ng (2013)
Blended EFBs	Aerobic Digestion	Bio-compost	0.95	Hubbe et al. (2010)
Blended EFBs	Alkaline Activation	Activated Carbon	0.50	Kaghazchi et al. (2006)
Blended EFBs	Extraction	Cellulose	0.63	Assumed value based on hemicellulose and lignin conversion factor
Blended EFBs	Extraction	Hemicellulose	0.18	www.ipst.gatech.edu
Blended EFBs	Extraction	Lignin	0.19	www.purelignin.com
Blended EFBs	Briquetting	Briquette	0.38	Ng and Ng (2013)
Blended EFBs	Pelletization	Pellet	0.38	Ng and Ng (2013)

Blended EFBs	Torrefied Pelletization	Torrefied Pellet	0.38	Ng and Ng (2013)

Table 4.12 Approximated CO_2 emission factor at *h*

Biomass type, *g*	**Pre-Processing, *h***	**Pre-processed product, *i***	**CO_2 emission factor (tonne CO_2 equivalent/tonne of product produced)**	**Reference**
Blended EFBs	DLF Production	Dry Long Fiber	0.0041	www.oecotextiles.wordpress.com
Blended EFBs	Aerobic Digestion	Bio-compost	0.0200	www.epa.gov
Blended EFBs	Alkaline Activation	Activated Carbon	0.0176	www.omnipure.com
Blended EFBs	Extraction	Cellulose	0.0590	Murillo-Alvarado et al. (2013)
Blended EFBs	Extraction	Hemicellulose	0.0650	Murillo-Alvarado et al. (2013)
Blended EFBs	Extraction	Lignin	0.0620	Assumed value based on values for cellulose and hemicellulose
Blended EFBs	Briquetting	Briquette	0.0500	Assumed value
Blended EFBs	Pelletization	Pellet	0.0500	Assumed value
Blended EFBs	Torrefied Pelletization	Torrefied Pellet	0.0805	Kaliyan et al. (2014)

Table 4.13 Approximated production cost factor at *j* in $ per tonne

Pre-processed feedstock, *i*	**Main processing, *j***	**Intermediate product 1, *k***	**$/Tonne**	**Reference**
Dry Long Fiber	Bio-composite Production	Bio-composite	107.0	ERIA (2014)
Cellulose	CMC Production	CMC	2500.0	www.trade.ec.europa.eu
Cellulose	Acid Hydrolysis	Glucose	73.4	Murillo-Alvarado et al. (2013)
Cellulose	Enzymatic Hydrolysis	Glucose	85.7	Murillo-Alvarado et al. (2013)
Hemicellulose	Acid Hydrolysis	Xylose	168.7	Murillo-Alvarado et al. (2013)
Hemicellulose	Enzymatic Hydrolysis	Xylose	83.1	Murillo-Alvarado et al. (2013)
Lignin	Resin Production	Bio-resin	1900.0	Chiarakorn et al. (2013)
Briquette	Boiler Combustion	HP Steam	20.7	www1.eere.energy.gov
Pellet	Boiler Combustion	HP Steam	20.7	www1.eere.energy.gov
Pellet	Gasification	Bio-syngas	300.0	Assumed value based on 50% of Bio-syngas price
Pellet	Fast pyrolysis	Bio-oil	1003	Thorp (2010)
Pellet	Slow pyrolysis	Bio-char	111.5	www.irena.org
Torrefied Pellet	Boiler Combustion	HP Steam	20.7	www1.eere.energy.gov
Torrefied Pellet	Gasification	Bio-syngas	300.0	Assumed value based on 50% of Bio-syngas price
Torrefied Pellet	Fast pyrolysis	Bio-oil	1003	Thorp (2010)

Table 4.14 Approximated conversion factor at *j*

Pre-processed feedstock, *i*	**Main processing, *j***	**Intermediate product 1, *k***	**Conversion factor**	**Reference**
Dry Long Fiber	Bio-composite Production	Bio-composite	0.75	Karbstein et al. (2013)
Cellulose	CMC Production	CMC	0.86	Saputra et al. (2014)
Cellulose	Acid Hydrolysis	Glucose	0.37	Murillo-Alvarado et al. (2013)
Cellulose	Enzymatic Hydrolysis	Glucose	0.47	Murillo-Alvarado et al. (2013)
Hemicellulose	Acid Hydrolysis	Xylose	0.91	Murillo-Alvarado et al. (2013)
Hemicellulose	Enzymatic Hydrolysis	Xylose	0.88	Murillo-Alvarado et al. (2013)
Lignin	Resin Production	Bio-resin	0.95	Yin et al. (2012)
Briquette	Boiler Combustion	HP Steam	0.20	Searcy and Flynn (2009)
Pellet	Boiler Combustion	HP Steam	0.25	Searcy and Flynn (2009)
Pellet	Gasification	Bio-syngas	0.70	Boerrigter and Drift (2005)
Pellet	Fast pyrolysis	Bio-oil	0.60	Zhang et al. (2013)
Pellet	Slow pyrolysis	Bio-char	0.50	www.biocharfarms.org
Torrefied Pellet	Boiler Combustion	HP Steam	0.30	Searcy and Flynn (2009)
Torrefied Pellet	Gasification	Bio-syngas	0.80	Boerrigter and Drift (2005)
Torrefied Pellet	Fast pyrolysis	Bio-oil	0.60	Zhang et al. (2013)

Table 4.15 Approximated CO_2 emission factor at *j*

Pre-processed feedstock, *i*	**Main processing, *j***	**Intermediate product 1, *k***	**CO_2 emission factor (tonne CO_2 equivalent/tonne of product produced)**	**Reference**
Dry Long Fiber	Bio-composite Production	Bio-composite	7.481	www.winrigo.com
Cellulose	CMC Production	CMC	0.097	Assumed value
Cellulose	Acid Hydrolysis	Glucose	0.097	Murillo-Alvarado et al. (2013)
Cellulose	Enzymatic Hydrolysis	Glucose	0.085	Murillo-Alvarado et al. (2013)
Hemicellulose	Acid Hydrolysis	Xylose	0.075	Murillo-Alvarado et al. (2013)
Hemicellulose	Enzymatic Hydrolysis	Xylose	0.082	Murillo-Alvarado et al. (2013)
Lignin	Resin Production	Bio-resin	2.500	www.netcomposites.com
Briquette	Boiler Combustion	HP Steam	0.750	www.sarawakenergy.com.my
Pellet	Boiler Combustion	HP Steam	0.750	Assumed value
Pellet	Gasification	Bio-syngas	0.680	Basu (2013)
Pellet	Fast pyrolysis	Bio-oil	0.580	Zhang et al. (2013)
Pellet	Slow pyrolysis	Bio-char	0.580	Zhang et al. (2013)
Torrefied Pellet	Boiler Combustion	HP Steam	0.750	Assumed value
Torrefied Pellet	Gasification	Bio-syngas	0.680	Basu (2013)

Torrefied Pellet	Fast pyrolysis	Bio-oil	0.580	Zhang et al. (2013)

Table 4.16 Approximated production cost factor at *l* in $ per tonne or per MWh

Intermediate product 1, *k*	**Further processing 1, *l***	**Intermediate product 2, *m***	**$/Tonne or MWh**	**Reference**
Bio-oil	Steam Reforming	Bio-hydrogen	455.0	Sarkar and Kumar et al. (2010)
Bio-oil	Bio-oil Upgrading	Bio-gasoline	1089.0	Wright and Brown (2011)
Bio-oil	Bio-oil Upgrading	Bio-diesel	918.0	Wright and Brown (2011)
Glucose	Fermentation	Bio-ethanol	98.2	Murillo-Alvarado et al. (2013)
Xylose	Fermentation	Bio-ethanol	98.2	Murillo-Alvarado et al. (2013)
Glucose	Anaerobic Digestion	Bio-gas	199.0	Assumed value for 50% less of the bio-gas price
Xylose	Anaerobic Digestion	Bio-gas	199.0	Assumed value for 50% less of the bio-gas price
Xylose	Xylitol Production	Xylitol	2100.0	Assumed value for 50% less of the xylitol price
HP Steam	Power Production	Electricity	58.9/MWh	Searcy and Flynn (2009)
HP Steam	Power Production	MP Steam	12.0	Assumed valued based on the steam price
HP Steam	Power Production	LP Steam	7.0	Assumed valued based on the steam price
Bio-syngas	Methanol Production	Bio-methanol	83.6	Murillo-Alvarado et al. (2013)
Bio-syngas	Separation	Bio-hydrogen	112	Schubert (2013)
Bio-syngas	FTL Productions	Bio-diesel	167.3	Murillo-Alvarado et al. (2013)
Bio-syngas	FTL Productions	Bio-gasoline	519.8	Wright and Brown (2011)

Table 4.17 Approximated conversion factor at *l*

Intermediate Product 1, *k*	**Further Processing 1, *l***	**Intermediate Product 2, *m***	**Conversion Factor**	**Reference**
Bio-oil	Steam Reforming	Bio-hydrogen	0.84	Dillich (2013)
Bio-oil	Bio-oil Upgrading	Bio-gasoline	0.40	Kim et al. (2011)
Bio-oil	Bio-oil Upgrading	Bio-diesel	0.20	Kim et al. (2011)
Glucose	Fermentation	Bio-ethanol	0.33	Murillo-Alvarado et al. (2013)
Xylose	Fermentation	Bio-ethanol	0.33	Murillo-Alvarado et al. (2013)
Glucose	Anaerobic Digestion	Bio-gas	0.70	Hubbe et al. (2010)
Xylose	Anaerobic Digestion	Bio-gas	0.70	Hubbe et al. (2010)
Xylose	Xylitol Production	Xylitol	0.70	Prakasham et al. (2009)
HP Steam	Power Production	Electricity	0.30 MWh/tonne of steam	www.turbinesinfo.com
HP Steam	Power Production	MP Steam	0.35	Ng and Ng (2013)
HP Steam	Power Production	LP Steam	0.35	Ng and Ng (2013)
Bio-syngas	Methanol Production	Bio-methanol	0.41	Murillo-Alvarado et al. (2013)
Bio-syngas	Separation	Bio-hydrogen	0.46	Murillo-Alvarado et al. (2013)
Bio-syngas	FTL Productions	Bio-diesel	0.71	Boerrigter and Drift (2005)
Bio-syngas	FTL Productions	Bio-gasoline	0.29	Assumed value from bio-diesel conversion factor

Table 4.18 Approximated CO_2 emission factor at *l*

Intermediate Product 1, *k*	**Further Processing 1, *l***	**Intermediate Product 2, *m***	**CO_2 emission factor (tonne CO_2 equivalent/tonne of product produced)**	**Reference**
Bio-oil	Steam Reforming	Bio-hydrogen	16.930	Zhang et al. (2013)
Bio-oil	Bio-oil Upgrading	Bio-gasoline	13.000	Zhang et al. (2013)
Bio-oil	Bio-oil Upgrading	Bio-diesel	13.000	Zhang et al. (2013)
Glucose	Fermentation	Bio-ethanol	0.098	Murillo-Alvarado et al. (2013)
Xylose	Fermentation	Bio-ethanol	0.098	Murillo-Alvarado et al. (2013)
Glucose	Anaerobic Digestion	Bio-gas	0.250	Whiting & Azapagic, (2014)
Xylose	Anaerobic Digestion	Bio-gas	0.250	Whiting & Azapagic, (2014)
Xylose	Xylitol Production	Xylitol	0.082	Assumed value based on value of xylose
HP Steam	Power Production	Electricity	0.050	Assumed value
HP Steam	Power Production	MP Steam	0.050	Assumed value
HP Steam	Power Production	LP Steam	0.050	Assumed value
Bio-syngas	Methanol Production	Bio-methanol	0.083	Murillo-Alvarado et al. (2013)
Bio-syngas	Separation	Bio-hydrogen	0.090	Murillo-Alvarado et al. (2013)
Bio-syngas	FTL Productions	Bio-diesel	0.067	Murillo-Alvarado et al. (2013)
Bio-syngas	FTL Productions	Bio-gasoline	0.639	Murillo-Alvarado et al. (2013)

Table 4.19 Approximated production cost factor at *n* in $ per tonne

Intermediate product 2, *m*	**Further processing 2, *n***	**Final product, *p***	**$/Tonne**	**Reference**
Bio-hydrogen	Ammonia Production	Ammonia	377	www.hydrogen.energy.gov
Bio-methanol	Formaldehyde Production	Formaldehyde	232	www.icis.com
Bio-ethanol	Bio-ethylene Production	Bio-ethylene	1200	www.irena.org

Table 4.20 Approximated conversion factor at *n*

Intermediate product 2, *m*	**Further processing 2, *n***	**Final product, *p***	**Conversion factor**	**Reference**
Bio-hydrogen	Ammonia Production	Ammonia	0.80	www.hydrogen.energy.gov
Bio-methanol	Formaldehyde Production	Formaldehyde	0.97	Chu et al. (1997)
Bio-ethanol	Bio-ethylene Production	Bio-ethylene	0.99	www.irena.org

Table 4.21 Approximated CO_2 emission factor at *n*

Intermediate product 2, *m*	**Further processing 2, *n***	**Final product, *p***	**CO_2 emission factor (tonne CO_2 equivalent/tonne of product produced)**	**Reference**
Bio-hydrogen	Ammonia Production	Ammonia	1.694	Jubb et al. (2006)
Bio-methanol	Formaldehyde Production	Formaldehyde	0.083	Assumed value
Bio-ethanol	Bio-ethylene Production	Bio-ethylene	1.400	www.irena.org

4.4 Formulation of the Optimization Model

Since the aim of this study was to optimize the supply chain of multi-products productions from EFB, profitability was selected as an economic potential indicator. Therefore, mathematical model was written as;

Maximize Profit =

Max (Sales of Products - Biomass cost - Transportation cost - Production cost - Emission treatment cost from transportation - Emission treatment cost from production) (4.1)

$$\text{Sales of products} = \sum_{p=1}^{P} Q_p * Product's\ selling\ price \tag{4.2}$$

$$Biomass\ cost = \sum_g^G F_g * EFB\ Cost \tag{4.3}$$

$$Transportation\ cost = \left(\sum_g^G \sum_h^H FTF_{g,h} * TCGH_{g,h}\right) + \left(\sum_h^H \sum_i^I \sum_j^J FTH_{h,i,j} * TCHIJ_{h,i,j}\right) + \left(\sum_j^J \sum_k^K \sum_l^L FTJ_{j,k,l} * TCJKL_{j,k,l}\right) + \left(\sum_l^L \sum_m^M \sum_n^N FTL_{l,m,n} * TCLMN_{l,m,n}\right) \tag{4.4}$$

$$Production\ cost = \left(\sum_h^H \sum_i^I FPH_{h,i} * PROCH_{h,i}\right) + \left(\sum_i^I \sum_j^J \sum_k^K FPJ_{i,j,k} * PROCJ_{i,j,k}\right) + \left(\sum_k^K \sum_l^L \sum_m^M FPL_{k,l,m} * PROCL_{k,l,m}\right) + \left(\sum_m^M \sum_n^N \sum_o^O FPN_{m,n,o} * PROCN_{m,n,o}\right) \tag{4.5}$$

$$Emission\ treatment\ cost\ from\ transportation = [\left(\sum_g^G \sum_h^H FTFE_{g,h}\right) + \left(\sum_h^H \sum_i^I \sum_j^J FTHE_{h,i,j}\right) + \left(\sum_j^J \sum_k^K \sum_l^L FTJE_{j,k,l}\right) + \left(\sum_l^L \sum_m^M \sum_n^N FTLE_{l,m,n}\right)] * Emission\ treatment\ cost\ per\ tonne\ CO2e \quad (4.6)$$

$$FTFE_{g,h} = FTF_{g,h} * ETCGH_{g,h} \qquad \forall_{g,h} \qquad (4.7)$$

$$FTHE_{h,i,j} = FTH_{h,i,j} * ETCHIJ_{h,i,j} \qquad \forall_{h,i,j} \qquad (4.8)$$

$$FTJE_{j,k,l} = FTJ_{j,k,l} * ETCJKL_{j,k,l} \qquad \forall_{j,k,l} \qquad (4.9)$$

$$FTLE_{l,m,n} = FTL_{l,m,n} * ETCLMN_{l,m,n} \qquad \forall_{l,m,n} \qquad (4.10)$$

$$Emission\ treatment\ cost\ from\ production = [\left(\sum_h^H \sum_i^I FPHE_{h,i}\right) + \left(\sum_i^I \sum_j^J \sum_k^K FPJE_{i,j,k}\right) + \left(\sum_k^K \sum_l^L \sum_m^M FPLE_{k,l,m}\right) + \left(\sum_m^M \sum_n^N \sum_o^O FPNE_{m,n,o}\right) * Emission\ treatment\ cost\ per\ tonne\ CO2e \quad (4.11)$$

$$FPHE_{h,i} = FPH_{h,i} * EPROCH_{h,i} \qquad \forall_{h,i} \qquad (4.12)$$

$$FPJE_{i,j,k} = FPJ_{i,j,k} * EPROCJ_{i,j,k} \qquad \forall_{i,j,k} \qquad (4.13)$$

$$FPLE_{k,l,m} = FPL_{k,l,m} * EPROCL_{k,l,m} \qquad \forall_{k,l,m} \qquad (4.14)$$

$$FPNE_{m,n.o} = FPN_{m,n,o} * EPROCN_{m,n,o} \qquad \forall_{m,n,o} \qquad (4.15)$$

For the inequality constraints, the amount of EFBs at each resource location must be not exceeding their availability. In addition, the demands for each of the products must be met. Both constraints are represented by (4.16) and (4.17), respectively.

$$\sum_g^G F_g \leq Biomass\ Availability \qquad (4.16)$$

$$Five\ percent\ of\ World\ Demands \geq Q_p \geq Product's\ Demand \qquad \forall_p \qquad (4.17)$$

Formulations for mass balances are represented by (4.18) through (4.27). Descriptions about each formulation in the model and terms are shown in Table 4.22 and Table 4.23, respectively.

$$\sum_{h}^{H} FTF_{g,h} \leq F_{g} \qquad \forall_{g} \tag{4.18}$$

$$\sum_{g}^{G} FTF_{g,h} * CONVH_{h,i} = FPH_{h,i} \qquad \forall_{h,i} \tag{4.19}$$

$$FPH_{h,i} = \sum_{j}^{J} FTH_{h,i,j} + FSH_{h,i} \qquad \forall_{h,i} \tag{4.20}$$

$$\sum_{h}^{H} FTH_{h,i,j} * CONVJ_{i,j,k} = FPJ_{i,j,k} \qquad \forall_{i,j,k} \tag{4.21}$$

$$\sum_{i}^{I} FPJ_{i,j,k} = FSJ_{j,k} + \sum_{l}^{L} FTJ_{j,k,l} \qquad \forall_{j,k} \tag{4.22}$$

$$\sum_{j}^{J} FTJ_{j,k,l} * CONVL_{k,l,m} = FPL_{k,l,m} \qquad \forall_{k,l,m} \tag{4.23}$$

$$\sum_{k}^{K} FPL_{k,l,m} = FSL_{l,m} + \sum_{n}^{N} FTL_{l,m,n} \qquad \forall_{l,m} \tag{4.24}$$

$$\sum_{l}^{L} FTL_{l,m,n} * CONVN_{m,n,o} = FPN_{m,n,o} \qquad \forall_{m,n,o} \tag{4.25}$$

$$\sum_{m}^{M} FPN_{m,n,o} = FSN_{n,o} \qquad \forall_{n,o} \tag{4.26}$$

$$\sum_{h}^{H} FSH_{h,i} + \sum_{j}^{J} FSJ_{j,k} + \sum_{l}^{L} FSL_{l,m} + \sum_{n}^{N} FSN_{n,o} = Q_{p} \qquad \forall_{i,k,m,o} \tag{4.27}$$

Table 4.22 Description about model's formulations in Chapter 4

Formulation	Description
(4.1)	Objective function
(4.2)	Total sales of products in $ per year
(4.3)	Total biomass cost in $ per year
(4.4)	Total transportation cost in $ per year
(4.5)	Total production cost in $ per year
(4.6)	Total emission treatment cost from transportations in $ per year
(4.7)	Emission from transportation between *g* and *h* in tonne CO_2e per year
(4.8)	Emission from transportation between *h* and *j* in tonne CO_2e per year
(4.9)	Emission from transportation between *j* and *l* in tonne CO_2e per year

(4.10)	Emission from transportation between *l* and *n* in tonne CO_2e per year
(4.11)	Total Emission treatment cost from productions in $ per year
(4.12)	Emission from production at *h* in tonne CO_2e per year
(4.13)	Emission from production at *j* in tonne CO_2e per year
(4.14)	Emission from production at *l* in tonne CO_2e per year
(4.15)	Emission from production at *n* in tonne CO_2e per year
(4.16)	Amount of EFB in tonne per year must not exceed availability
(4.17)	Range of amount of produced product in tonne or MWh per year
(4.18)	Mass balance for EFB storages outlet in tonne per year
(4.19)	Mass balance for yield of pre-processed feedstocks in tonne per year
(4.20)	Mass balance for pre-processing facilities outlet in tonne per year
(4.21)	Mass balance for yield of intermediate products 1 in tonne per year
(4.22)	Mass balance for main processing facilities outlet in tonne per year
(4.23)	Mass balance for yield of intermediate products 2 in tonne or MWh per year
(4.24)	Mass balance for further processing facilities 1 outlet in tonne per year
(4.25)	Mass balance for yield of final products in tonne per year
(4.26)	Mass balance for further processing facilities 2 outlet in tonne per year
(4.27)	Summation of sales for all products at *h*, *j*, *l*, and *n*

Table 4.23 Descriptions of terms used in (4.1) till (4.27)

Term	Category	Description
$TCGH_{g,h}$	Parameter	Transportation cost factor for biomass feedstock from g to *h* in $ per tonne
$ETCGH_{g,h}$	Parameter	CO_2 emission factor for EFB feedstock transported from *g* to *h*
$TCHIJ_{h,i,j}$	Parameter	Transportation cost factor for pre-processed feedstock from *h* to *j* through *i* in $ per tonne
$ETCHIJ_{h,i,j}$	Parameter	CO_2 emission factor for pre-processed feedstock transported from *h* to *j*
$TCJKL_{j,k,l}$	Parameter	Transportation cost factor for intermediate product 1 from *j* to *l* through *k* in $ per tonne
$ETCJKL_{j,k,l}$	Parameter	CO_2 emission factor for intermediate product 1 transported from *j* to *l*
$TCLMN_{l,m,n}$	Parameter	Transportation cost factor for intermediate product 2 from *l* to *n* through *m* in $ per tonne
$ETCLMN_{l,m,n}$	Parameter	CO_2 emission factor for intermediate product 2 transported from *l* to *n*
$PROCH_{h,i}$	Parameter	Production cost factor at *h* to produce *i* from *g* in $ per tonne
$EPROCH_{h,i}$	Parameter	CO_2 emission factor at production *h*
$PROCJ_{i,j,k}$	Parameter	Production cost factor at *j* to produce *k* from *i* in $ per tonne
$EPROCJ_{i,j,k}$	Parameter	CO_2 emission factor at production *j*
$PROCL_{k,l,m}$	Parameter	Production cost factor at *l* to produce *m* from *k* in $ per tonne or per MWh
$EPROCL_{k,l,m}$	Parameter	CO_2 emission factor at production *l*
$PROCN_{m,n,o}$	Parameter	Production cost factor at *n* to produce *o* from *m* in $ per tonne
$EPROCN_{m,n,o}$	Parameter	CO_2 emission factor at production *n*
$CONVH_{h,i}$	Parameter	Conversion factor at *h* to produce *i*
$CONVJ_{i,j,k}$	Parameter	Conversion factor at *j* to produce *k* from *i*
$CONVL_{k,l,m}$	Parameter	Conversion factor at *l* to produce *m* from *k*
$CONVN_{m,n,o}$	Parameter	Conversion factor at *n* to produce *o* from *m*
Q_p	Decision variable	Sum up of products from each of product storage in tonne or MWh per year

F_g	Decision variable	Amount of biomass available at resource location and stored in tonne per year
$FTF_{g,h}$	Decision variable	Amount of biomass transported to pre-processing facilities *h* in tonne per year
$FTFE_{g,h}$	Decision variable	Amount of emission from transportation between g and h in tonne CO_2 equivalent per year
$FTH_{h,i,j}$	Decision variable	Amount of pre-processed feedstocks *i* transported from pre-processing facilities *h* to main processing facilities *j* in tonne per year
$FSH_{h,i}$	Decision variable	Amount of pre-processed feedstocks *i* produced from pre-processing facilities *h* to be sold directly in tonne per year
$FTHE_{h,i,j}$	Decision variable	Amount of emission from transportation between *h* and *j* in tonne CO_2 equivalent per year
$FTJ_{j,k,l}$	Decision variable	Amount of intermediate products 1 *k* transported from main processing facilities *j* to further processing 1 facilities *l* in tonne per year
$FSJ_{j,k}$	Decision variable	Amount of intermediate products 1 *k* produced from main processing facilities *j* to be sold directly in tonne per year
$FTJE_{j,k,l}$	Decision variable	Amount of emission from transportation between *j* and *l* in tonne CO_2 equivalent per year
$FTL_{l,m,n}$	Decision variable	Amount of intermediate products 2 *m* transported from further processing 1 facilities *l* to further processing 2 facilities *n* in tonne per year
$FSL_{l,m}$	Decision variable	Amount of intermediate products 2 *m* produced from intermediate products 1 *k* through further processing 1 facilities *l* to be sold directly in tonne per year
$FTLE_{l,m,n}$	Decision variable	Amount of emission from transportation between l and n in tonne CO_2 equivalent per year
$FSN_{n,o}$	Decision variable	Amount of final products *o* produced from intermediate products 2 *m* through further processing 2 facilities *n* to be sold in tonne per year
$FPH_{h,i}$	Decision variable	Amount of pre-processed feedstocks *i* produced from biomass feedstocks *g* through pre-processing facilities *h* in tonne per year
$FPHE_{h,i}$	Decision variable	Amount of emission from production at *h* in tonne CO_2 equivalent per year
$FPJ_{i,j,k}$	Decision variable	Amount of intermediate product 1 *k* produced from pre-processed feedstocks *i* through main processing facilities *j* in tonne per year
$FPJE_{i,j,k}$	Decision variable	Amount of emission from production at j in tonne CO_2 equivalent per year
$FPL_{k,l,m}$	Decision variable	Amount of intermediate products 2 *m* produced from intermediate products 1 *k* through further processing 1 facilities *l* in tonne or MWh per year
$FPLE_{k,l,m}$	Decision variable	Amount of emission from production at l in tonne CO_2 equivalent per year

$FPN_{m,n,o}$	Decision variable	Amount of final products *o* produced from intermediate products 2 *m* through further processing 2 facilities *n* in tonne per year
$FPNE_{m,n.o}$	Decision variable	Amount of emission from production at n in tonne CO_2 equivalent per year

4.5 Results and Discussions

The developed optimization model for the multi-products productions from EFB was executed in GAMS Rev 149, using CPLEX 11.0.0 as a solver. The solution was performed in AMD A10-4600M APU processor and contained 42 blocks of equations, 31 blocks of variables, 5401 single equations, 6844 single variables and took 0.079 seconds to solve. For the given parameters, the optimal profit was found to be $ 713,642,269 per year for a single ownership of all facilities in the EFB's supply chain. Table 4.24 shows optimal level of productions for all products which utilized 1900400.458, 6451782.271 and 21052.632 tonnes per year of EFBs from Johore, Pahang and Perak, respectively. As was mentioned earlier, blending of EFBs were assumed so that it could meet the supply requirements to the pre-processing facilities. In addition, optimization results have determined portions of the produced products whether to be further processed or to be sold directly depending on the economic profitability. Table 4.25 shows distributions of EFB sources to the respective pre-processing facilities.

Table 4.24 Optimal production level of products

Product	Production (tonne per year or MWh per year)
DLF	2302323.090
Bio-compost	20000.000
Activated carbon	95000.000
Cellulose	134363.904
Hemicellulose	37862.333
Lignin	30000.000
Briquette	30.000
Pellet	37.000
Torrefied pellet	70.000
Bio-composite	0.920
CMC	0.400
Glucose	5.810
Xylose	15.000
Bio-resin	10000.000
HP steam	2.000
Bio-syngas	462000.000
Bio-oil	5.000
Bio-char	3000.000
Bio-hydrogen	375.500
Xylitol	0.002

Bio-ethanol	3.600
Bio-gas	9.000
Bio-methanol	0.300
Electricity	20.000
MP Steam	23.333
LP Steam	23.333
Bio-ethylene	140.000
Bio-diesel	40000.000
Bio-gasoline	16338.028
Ammonia	170.000
Formaldehyde	42.000

Table 4.25 Amount of EFB biomass transported to pre-processing facilities h, $FTF_{g,h}$ (tonne per year)

Biomass source	**DLF production**	**Aerobic digestion**	**Alkaline activation**	**Extraction**	**Briquetting**	**Pelletization**	**Torrefied pelletization**
EFB collection 1 (Johore)	-	-	190000.000	-	-	-	1710400.458
EFB collection 2 (Pahang)	6222498.153	-	-	213296.399	78.947	15908.772	-
EFB collection 3 (Perak)	-	21052.632	-	-	-	-	-

Next, from the pre-processing facilities, the pre-processed products would have two options in which either to be processed in the main processing facilities or to be purchased by the users directly. These are shown by Table 4.26 and Table 4.27, respectively. For example, considering demand and EFB's availability, it was more economical to sell dry long fiber (DLF) than to send it the next stage of processing. These were similar cases for cellulose, hemicellulose and lignin at the given parameters. Oppositely, the results indicated that it was more economical to process torrefied pellet in the main processing facilities (gasification and boiler combustion) than to sell it directly. Furthermore, summation of the portions to be sent for main processing and the portions to be sold are equal to the amount of pre-processed feedstocks produced by the respective pre-processing facility.

Table 4.26 Amount of pre-processed feedstocks i transported from pre-processing facilities h to main processing facilities j, $FTH_{h,i,j}$ (tonne per year)

Path	Bio-composite production	CMC production	Acidic hydrolysis	Enzymatic hydrolysis	Resin production	Boiler combustion	Gasification	Fast pyrolysis	Slow pyrolysis
DLF from DLF production	1.227	-	-	-	-	-	-	-	-
Cellulose from extraction	-	0.465	-	12.362	-	-	-	-	-
Hemicellulose from extraction	-	-	0.003	531.016	-	-	-	-	-
Lignin from extraction	-	-	-	-	10526.316	-	-	-	-
Torrefied pellet from torrefied pelletization	-	-	-	-	-	228.889	649653.285	-	-
Pellet from pelletization	-	-	-	-	-	8.333	-	-	6000.00

Table 4.27 Amount of pre-processed feedstocks i produced from pre-processing facilities h to be sold directly, $FSH_{h,i}$ (tonne per year)

Path	Amount to be sold directly (tonne/year)	Sales of products ($/year)
DLF from DLF production	2302323.090	483487848.9
Bio-compost from aerobic digestion	20000.000	2000000.0
Activated carbon from alkaline activation	95000.000	166820000.0
Cellulose from extraction	134363.904	295600588.8
Hemicellulose from extraction	37862.333	75724666.0

Lignin from extraction	30000.000	45000000.0
Briquette from briquetting	30.00	3600
Pellet from pelletization	37.00	5180
Torrefied pellet from torrefied pelletization	70.00	11200

After exiting the main processing facilities, the intermediate products 1 again would either be sending for next processing step (further processing facilities 1) or to be sold directly. Table 4.28 and Table 4.29 show the both options, respectively. The amounts of bio-syngas from gasification was shown by the model's results to be sold directly in preference over to further refine it in methanol production, separation and FTL production facilities. Since there was no further processing for bio-resin as shown in the superstructure, it would be automatically sold directly to the customer.

Table 4.28 Amount of intermediate products 1 k transported from main processing facilities j to further processing 1 facilities l, $FTJ_{j,k,l}$ (tonne per year)

Path	**Separation**	**Xylitol production**	**Fermentation**	**Anaerobic digestion**	**Power production**	**Methanol production**	**FTL production**
Xylose from acidic hydrolysis	-	0.003	-	-	-	-	-
Xylose from enzymatic hydrolysis	-	-	439.437	12.857	-	-	-
Bio-syngas from gasification	1278.261	-	-	-	-	106.339	56338.028
HP steam from boiler combustion	-	-	-	-	66.667	-	-

Table 4.29 Amount of intermediate products 1 *k* produced from main processing facilities *j* to be sold directly,
$FSJ_{j,k}$ (tonne per year)

Path	**Amount to be sold directly (tonne/year)**	**Sales of products ($/year)**
Bio-composite from bio-composite production	0.920	575.0
CMC from CMC production	0.400	1400.0
Glucose from enzymatic hydrolysis	5.810	10980.9
Xylose from enzymatic hydrolysis	15.000	29850.0
Bio-resin from resin production	10000	90720000.0
HP Steam from boiler combustion	2.00	52.0
Bio-syngas from gasification	462000.00	277200000.0
Bio-oil from fast pyrolysis	5.000	4000.0
Bio-char from slow pyrolysis	3000.00	1140000

The further processing 1 facilities will produce intermediate products 2. These intermediates need to be further processed or the manufactures can sell them directly to fulfill the specified demands. Table 4.30 and Table 4.31 show these options. At this point, majority of the produced products would be sold directly as no further processing required except for the portions of bio-hydrogen, bio-ethanol and bio-methanol. Furthermore, with the given parameters, product such as xylitol could be neglected for production especially if the demand is too low.

Table 4.30 Amount of intermediate products 2 *m* transported from further processing 1 facilities *l* to further processing 2 facilities *n*,
$FTL_{l,m,n}$ (tonne per year)

Path	**Ammonia production**	**Formaldehyde production**	**Bio-ethylene production**
Bio-hydrogen from steam reforming	212.500	-	-
Bio-ethanol from fermentation	-	-	141.414

Bio-methanol from methanol production	-	43.229	-

Table 4.31 Amount of intermediate products 2 *m* produced from intermediate products 1 *k* through further processing 1 facilities *l* to be sold directly, $FSL_{l,m}$ (tonne or MWh per year)

Path	Amount to be sold directly (tonne/year)	Sales of products ($/year)
Bio-hydrogen from steam reforming	375.500	307159.0
Xylitol from xylitol production	0.002	8.4
Bio-ethanol from fermentation	3.600	1882.8
Bio-gas from anaerobic digestion	9.000	3582.0
Bio-methanol from methanol production	0.300	261.0
Electricity from power production	20.000	2800.0
MP Steam from power production	23.333	396.6
LP Steam from power production	23.333	280.0
Bio-diesel from FTL production	40000.000	31600000.0
Bio-gasoline from FTL production	16338.028	21484506.8

Finally, the further processing 2 facilities will produce the final products. These three products are then ready to be shipped for selling as shown by Table 4.32.

Table 4.32 Amount of final products o produced from intermediate products 2 m through further processing 2 facilities n to be sold,
$FSN_{n,o}$ (tonne per year)

Path	Amount (Tonne/year)	Sales of products ($/year)
Ammonia from ammonia production	170.000	126650.0
Formaldehyde from formaldehyde production	42.000	19446.0
Bio-ethylene from bio-ethylene production	140.000	216160.0

The amount of emissions from transportation and production were the result of multiplications between the emission factors and the mass flowrates. Having said this, the owner of the EFB's facilities would be aware of which transportation segments and production facilities have emitted large amounts of CO_2 equivalent per year despite the optimal overall profitability has considered the emission treatment costs. Table 4.33 till 4.39 tabulate these emission results that originated from transportations and productions.

Table 4.33 Amount of emission from transportation between g and h in tonne CO_2 equivalent per year,
$FTFE_{g,h}$

Biomass source	DLF production	Aerobic digestion	Alkaline activation	Extraction	Briquetting	Pelletization	Torrefied pelletization
EFB collection 1 (Johore)	-	-	874.000	-	-	-	7867.842
EFB collection 2 (Pahang)	22400.993	-	-	1087.812	0.284	68.408	-

Table 4.34 Amount of emission from transportation between *h* and *j* in tonne CO_2 equivalent per year,

$FTHE_{h,i,j}$

Path	Bio-composite production	Acidic hydrolysis	Enzymatic hydrolysis	Resin production	Boiler combustion	Gasification	Slow pyrolysis
DLF from DLF production	0.002	-	-	-	-	-	-
Cellulose from extraction	-	-	0.085	-	-	-	-
Hemicellulose from extraction	-	3.768×10^{-5}	3.664	-	-	-	-
Lignin from extraction	-	-	-	89.474	-	-	-
Torrefied pellet from torrefied pelletization	-	-	-	-	0.320	3118.336	-
Pellet from pelltization	-	-	-	-	-	-	45.600

Table 4.35 Amount of emission from transportation between *j* and *l* in tonne CO_2 equivalent per year,

$FTJE_{j,k,l}$

Path	Fermentation	Anaerobic digestion
Xylose from enzymatic hydrolysis	1.758	0.030

Table 4.36 Amount of emission from production at *h* in tonne CO_2 equivalent per year,

$FPHE_{h,i}$

Product	DLF production	Aerobic digestion	Alkaline activation	Extraction	Briquetting	Pelletization	Torrefied pelletization
DLF from	9439.530	-	-	-	-	-	-
Bio-compost from	-	400.000	-	-	-	-	-
Activated carbon from	-	-	1672.000	-	-	-	-
Cellulose from	-	-	-	7928.227	-	-	-

Hemicellulose from	-	-	-	2495.568	-	-	-
Lignin from	-	-	-	2512.632	-	-	-
Briquette from					1.500		
Pellet from						302.267	
Torrefied pellet from							52321.150

Table 4.37 Amount of emission from production at j in tonne CO_2 equivalent per year, $FPJE_{i,j,k}$

Product	**DLF in bio-composite production**	**Cellulose in CMC production**	**Cellulose in enzymatic hydrolysis**	**Hemicellulose in acid hydrolysis**	**Hemicellulose in enzymatic hydrolysis**	**Lignin in resin production**	**Torrefied pellet in boiler combustion**	**Torrefied pellet in gasification**	**Pellet in fast pyrolysis**	**Pellet in slow pyrolysis**
Bio-composite from	6.883	-	-	-	-	-	-	-		-
CMC from	-	0.039	-	-	-	-	-	-		-
Glucose from	-	-	0.494	-	-	-	-	-		-
Xylose from	-	-	-	2.143×10^{-4}	38.318	-	-	-		-
Bio-resin from	-	-	-	-	-	25000.000	-	-		-
HP steam from	-	-	-	-	-	-	51.500	-		-
Bio-syngas from	-	-	-	-	-	-	-	353931.110		-
Bio-oil from	-	-	-	-	-	-	-	-	2.900	-
Bio-char from	-	-	-	-	-	-	-	-	-	1740.000

Table 4.38 Amount of emission from production at l in tonne CO_2 equivalent per year, $FPLE_{k,l,m}$

Product	Bio-syngas in steam separation	Xylose in xylitol production	Xylose in fermentation	Xylose in aerobic digestion	Bio-syngas in methanol production	HP steam in power production	Bio-syngas in FTL production
Bio-hydrogen from	52.920	-	-	-	-	-	-
Xylitol from	-	1.640×10^{-4}	-	-	-	-	-
Bio-ethanol from	-	-	14.211	-	-	-	-
Bio-gas from	-	-	-	2.250	-	-	-
Bio-methanol from	-	-	-	-	3.619	-	-
Electricity from	-	-	-	-	-	1.000	-
MP steam from	-	-	-	-	-	1.167	-
LP steam from	-	-	-	-	-	1.167	-
Bio-diesel from	-	-	-	-	-	-	2680.000
Bio-gasoline from	-	-	-	-	-	-	10440.000

Table 4.39 Amount of emission from production at n in tonne CO_2 equivalent per year, $FPNE_{m,n.o}$

Product	Bio-ethanol in bio-ethylene production	Bio-hydrogen in ammonia production	Bio-methanol in formaldehyde production
Bio-ethylene	196.000	-	-
Ammonia	-	287.980	-
Formaldehyde	-	-	3.486

From these results, economic decision could be made in a more guided way especially in prioritizing investments for productions. Facility owner was also being informed with potential emissions from both transportation and production activities. In addition, the owner was flexible in making decision on whether to sell the produced product directly or to further processing it based on the market situations.

4.6 Sensitivity Analysis

Sensitivity analysis were performed by varying the selling prices for three selected products i.e bio-hydrogen, ammonia and bio-ethylene. Other products could be selected as well because the purpose of this analysis was to observe effects on the objective function by manipulating the model's parameter. Three scenarios were created to demonstrate these effects as shown in Table 4.40. It can be seen that the variations in selling prices, which might happen due to changes in demands have definitely affected the original recorded profit.

Table 4.40 Sensitivity analysis for the profitability ($/year) of the selected bio-products with selling prices' variations

Scenario in selling price for the three products	Difference in annual profit ($/year)
Scenario 1: All bio-hydrogen, ammonia and bio-ethylene have shown 10% increase in selling price	+64997
Scenario 2: Bio-hydrogen has shown 10% increase, ammonia has decreased 10% and bio-ethylene remain the same	+18051
Scenario 3: Only bio-ethylene has decreased 10%	-21616

4.7 Conclusion and Future Works

The economic potentials of exploiting palm oil EFB as renewable feedstocks for the productions of products that range from energy, chemicals and materials were realized by having the optimal supply chain. Pre-requisite steps for obtaining the optimal supply chain were presented, and those steps would still be applicable when dealing with different kind of biomass feedstocks and products. The parameters used in the model were approximated from various literature sources and were sufficient to illustrate the applicability of the model. By considering single ownership of all facilities in the EFB's supply chain, informed decision could be made to prioritize investments for manufacturing profitable products.

For the future works, this model will be further developed to include optimal selections of processing route and transportation mode.

Chapter 5

Multi-products Productions from Malaysian Oil Palm Empty Fruit Bunch (EFB): Selection for Optimal Process and Transportation Mode

5.1 Abstract

In Malaysia, palm oil industries have played significant roles in the economic sectors and for the nation’s developments as a whole. One aspect of these industries that is gaining growing interests is oil palm residues management and bio-based products generations. EFB has been identified to be a feasible raw material for productions of bio-energy, bio-chemicals and bio-materials. In this chapter, previous deterministic model was extended to include decisions for selecting optimal transportation modes and processes at each level of processing stage in the supply chain. The superstructure was modified to show states of produced products whether solid, liquid or gaseous, in which truck, train, barge or pipeline would be possible optimal mode of transportations. The objective function was to maximize profit that has counted associated costs including the emission treatment costs from productions and transportations. The optimal profit was $ 1,561,106,613 per year for single ownership of all facilities in the supply chain.

5.2 Introduction

Palm oil industries have played significant roles for the socio-economic developments in Malaysia. Since 1960, Malaysia has been one of the major producer and exporter of palm oil (Alang Mahat, 2012). Statistics showed that the palm oil sector has contributed 12% of the total Malaysia’s export and this percentage was equivalent to RM 80.4 billion or about USD 22.08 billion (May, 2011). In terms of social and rural improvements, the establishment of Federal Land Development Authority (FELDA) in 1956 has carried out landless resettlements mainly for palm oil plantations in the country that benefited almost 113000 low-income families (www.palmoilworld.org). This effort has not only alleviated poverty in the country but also reduced economic imbalances between urban and rural populations (Simeh and Tengku Ahmad, 2001).

As one of the most important sources of vegetables oils, palm oil demands are increasing with the proliferative growth of human populations globally. Interestingly, significant uses of palm oils for cooking and manufacturing oleo-chemicals have been annexed with the production of biodiesel recently. In this context, Malaysian's Ministry of Plantation Industries and Commodities has mandated to blend 7% of palm-based biodiesel with petro-based diesel instead of 5% blending before November 2014. This move has further increased economic gains of palm oil especially in the situations where petroleum prices are unduly high.

Palm oil plantations also produce agricultural biomass such as EFB. Although it has been once considered as a low value agricultural residue, technological advances started to convert this biomass into numerous types of bio-based products. The scenario has created considerable amounts of enterprising companies to venture into these waste-to-wealth businesses throughout the country. However, in order to plan and operate of any EFB's utilization project successfully, the supply chain that include optimal decision for process and transportation is one of the key consideration. With numerous alternatives available, selecting best processing route for producing a product is an important decision to make because of several factors associated with that such as product's competitiveness, viability and status of technology, social and environmental impacts, and so on. In this regards, Figure 5.1 depicts technological and resource-to-product selection dilemmas that typically occur in any biomass supply chain. Furthermore, it also has options to sell the produced product directly or to further refine it as shown by the dash line in this figure.

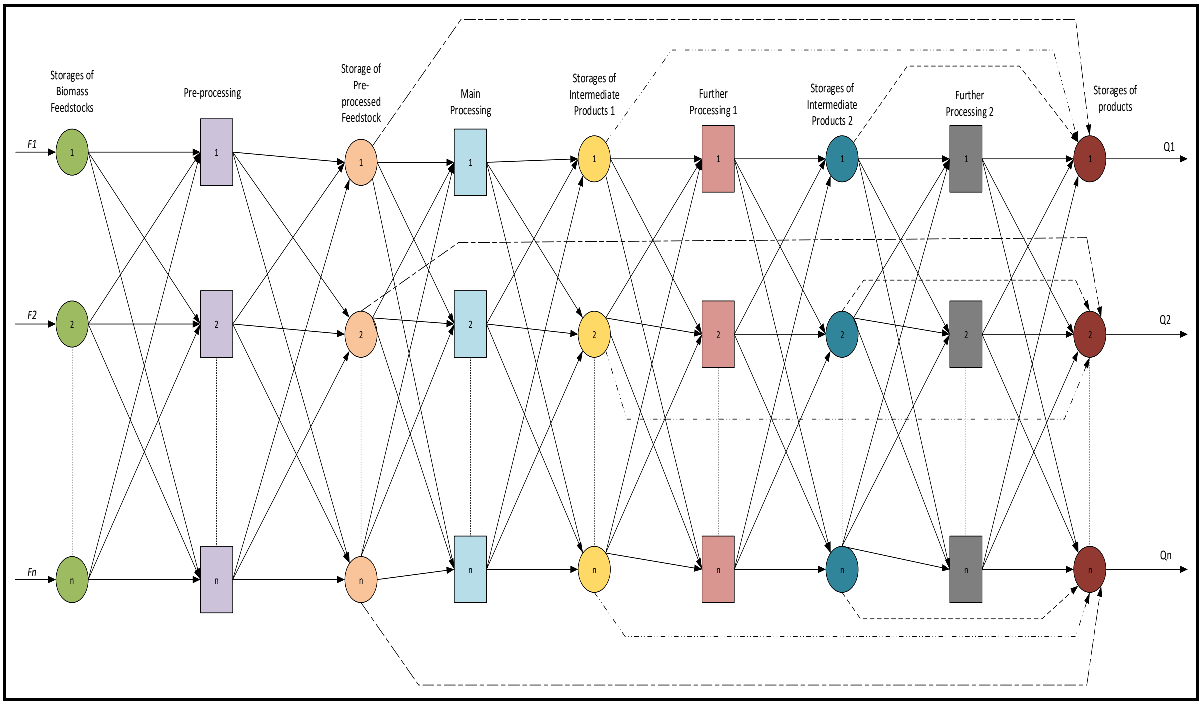

Figure 5.1 Selection dilemmas in biomass supply chain

The optimal decisions about transportation amounts and modes are meanwhile have directly influenced the overall economic profitability as well as biomass accessibility and mobility. Questions may arise whether to use truck, train, barge or by pipeline for transporting biomass and derived products from processing facility to the desired destination in the most economical way. Based on these reasons, the development of deterministic optimization model with integer decision is imperative and would be a focus for this study. The classification for this type of modeling is Mixed Integer Programming (MIP) which could be linear or non-linear.

Previous studies about MIP modeling of biomass supply chain have been published by several authors. These included a modelling of biomass sources for energy purposes through combustion (Nagel, 2000), a hybrid of gasification and fermentation processes of agricultural residues and dedicated crops for bio-ethanol production (Gelson et al., 2003), bio-ethanol production from agricultural residues and municipal solid wastes by considering policy standards and conversion technologies (Huang et al., 2010), agricultural residues for bio-ethanol production via bio-chemical route only by considering enzymatic hydrolysis and acidic hydrolysis (Marvin et al., 2011), multi-objective optimization for gasoline and bio-diesel productions by using combinations of forestry residues, agricultural residues and dedicated crops (You and Wang, 2011), and oil seed crop for the productions of energy products such as biodiesel, heat, power and syngas (Bowling et al., 2011). For recent studies, Zhang and Hu (2013) have modeled biofuel supply chain from corn stover by using fast pyrolysis process. They have considered different biomass supplies and demands with biofuel supply shortage penalty and storage cost in the model. Lin et al., (2014) have optimized biofuel supply chain model that integrates strategic and tactical planning decisions. Key strategic decisions were numbers, locations, capacities, and distribution patterns for biomass and ethanol, while biomass production and delivery were among the tactical decisions. Paulo et al., (2015) have developed an optimization model of supply chain for bioelectricity production from forest residues in Portugal. The objective function has minimized the total supply chain cost and optimally selected biomass amounts and sources.

The above-mentioned studies have modeled the biomass supply chain problem as Mixed Integer Linear Programming (MILP), while this chapter has involved with Mixed Integer Non-linear Programming (MINLP). The objective was to maximize the profit of EFB's supply chain for multi-products productions which would provide optimal decisions regarding biomass amounts, process and production levels, product's direct sales or further refinements, transportation modes at each processing stages, as well as environmental considerations from both productions and transportations. The model has again considered Peninsula Malaysia as a case study. Three collection sources of EFBs were taken from Johore, Pahang and Perak.

5.3 Methodology

In order to model and optimize the EFB's supply chain, methodology that is shown in Figure 5.2 was followed. This study has extended the previous optimization model to include integer variables for important decisions related to selections of best processes and transportation modes. Each decision was effective for each processing stage (pre-processing, main processing, further processing 1 and further processing 2) in the supply chain.

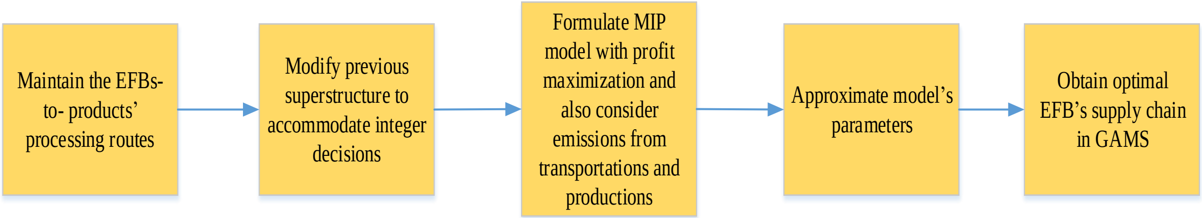

Figure 5.2 Methodology for EFB's supply chain with optimal processing route and transportation mode

Figure 5.3 shows the modified superstructure of EFB's supply chain. Each segment of transportation was assigned with relevant modes of transportations. Solid biomass and products transportations to the next processing stages would be utilize either truck, train or barge, while transportation of liquid or gaseous products would use pipeline automatically. Square shapes in the superstructure represent processing facilities while storages are represented by the oval shapes. The black solid arrows show processing sequences while the black dash lines give indications to sell the products from storage directly to the customers. Extraction process was divided into three (extraction 1, 2, and 3), acid hydrolysis into two (acid hydrolysis 1 and 2), enzymatic process into two (enzymatic hydrolysis 1 and 2), bio-oil upgrading into two (bio-oil upgrading 1 and 2), and lastly FTL production into two (FTL production 1 and 2). These divisions have involved for a square shape with more than one product except for power production which the products (electricity, MP steam and LP steam) were produced from a single unit process. The reason behind these divisions was to ensure the model could decide the optimal processing routes and their transportation modes, as well as the explanations could be established clearly. Similar to the previous superstructure, it shows competitive utilizations and routes for EFB, cellulose, hemicellulose, pellet, torrefied pellet, glucose, xylose, bio-syngas, and bio-oil. In addition, it has assumed for homogenous blending of EFBs from different collection points.

Overall, there were four stages of processing *(h*, *j*, *l*, and *n*) and four segments of transportations (*g* to *h*, *h* to *j*, *j* to *l*, and *l* to *n*). Table 5.1 lists the indices which will be used in the model's formulations.

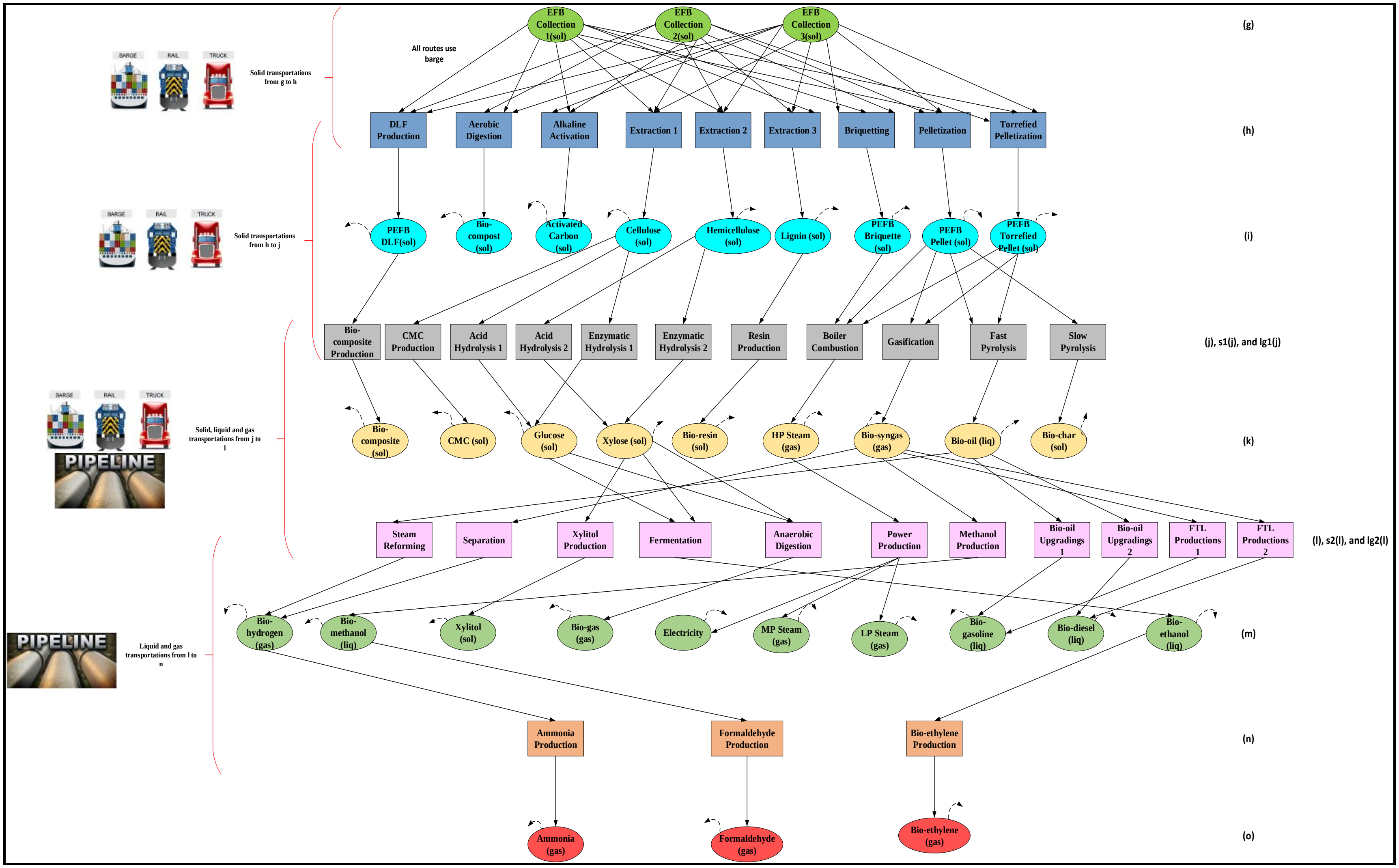

Figure 5.3 Superstructure of EFB's supply chain for selecting optimal processing routes and transportation mode

Table 5.1 List of indices and descriptions for model's formulations

Indices	**Description**	**Contents**
g	Biomass source storage locations	EFB1, EFB2 and EFB3
h	Pre-processing facilities	DLF production, aerobic digestion, alkaline activation, extraction 1, extraction 2, extraction 3, briquetting, pelletization, and torrefied pelletization.
j	Main processing facilities	Bio-composite production, CMC production, acid hydrolysis 1, acid hydrolysis 2, enzymatic hydrolysis 1, enzymatic hydrolysis 2, resin production, boiler combustion, gasification, fast pyrolysis, and slow pyrolysis.
s1(j)	Main processing facilities for solid products to the next processing facilities	Acid hydrolysis 1, acid hydrolysis 2, enzymatic hydrolysis 1 and enzymatic hydrolysis 2
lg1(j)	Main processing facilities for liquid and gaseous products to the next processing facilities	Boiler combustion, gasification, and fast pyrolysis.
l	Further processing 1 facilities	Steam reforming, separation, xylitol production, fermentation, anaerobic digestion, power production, methanol production, bio-oil upgrading 1, bio-oil upgrading 2, FTL production 1 and FTL production 2.
s2(l)	Further processing 1 facilities for solid feeds.	Xylitol production and anaerobic digestion.
lg2(l)	Further processing 1 facilities for solid solution, liquid and gaseous feeds.	Steam reforming, separation, power production, MP steam production, LP steam production, methanol production, bio-oil upgrading 1, bio-oil upgrading 2, FTL production 1, FTL production 2, and fermentation.
n	Further processing 2 facilities	Ammonia production, formaldehyde production, and bio-ethylene production.
t	Truck, train and barge transportation	Truck, train and barge.
z	Pipeline transportation	Pipeline.
p	Product sum up type p storages and to the users	PEFB-DLF, bio-compost, activated carbon, cellulose, hemicellulose, lignin, PFB briquette, PEFB pellet, PEFB torrefied pellet, bio-composite, CMC, glucose, xylose, bio-resin, HP steam, bio-syngas, bio-oil, bio-char, bio-hydrogen, xylitol, bio-ethanol, bio-gas, bio-methanol, electricity, MP steam, LP steam, bio-

		ethylene, bio-diesel, bio-gasoline, ammonia, and formaldehyde.
i(p)	Pre-processed feedstocks storages	PEFB-DLF, bio-compost, activated carbon, cellulose, hemicellulose, lignin, PFB briquette, PEFB pellet, and PEFB torrefied pellet.
k(p)	Intermediate products 1 storages	Bio-composite, CMC, glucose, xylose, bio-resin, HP steam, bio-syngas, bio-oil, and bio-char.
m(p)	Intermediate products 2 storages	Bio-hydrogen, xylitol, bio-ethanol, bio-gas, bio-methanol, electricity, MP steam, LP steam, bio-diesel, and bio-gasoline.
o(p)	Final products storages	Ammonia, formaldehyde, and bio-ethylene.

5.4 Mathematical Model for Optimal Selections

Formulations of mathematical model to optimize the EFB's supply chain were written by the following formulations, which were explained each of them in Table 5.2 and 5.3.

Maximize Profit = Maximize (Sales of products - Biomass cost - Transportation operating cost - Production cost - Emission treatment cost) (5.1)

$$\textit{Sales of products} = \sum_{p=1}^{P} Q_p * Products'\ selling\ price \tag{5.2}$$

$$Biomass\ cost = \sum_{g}^{G} F_g * EFB\ Cost \tag{5.3}$$

Transportation operating cost = Truck, train and barge transportation operating cost + pipeline transportation operating cost (5.4)

$$Truck, train\ and\ barge\ transportation\ operating\ cost = \sum_{t}^{T}((OPCOSTM_t * \sum_{g}^{G}\sum_{h}^{H} FTFT_{g,h,t} * 2 * DGH_{g,h}) + (OPCOSTM_t * \sum_{h}^{H}\sum_{j}^{J} FTHT_{h,j,t} * 2 * DHIJ_{h,j}) + (OPCOSTM_t * \sum_{j}^{J}\sum_{s2}^{S2} FTJT\_S_{j,s2,t} * 2 * DJKL\_S_{j,s2})) \tag{5.5}$$

$$Pipeline\ transportation\ operating\ cost = \sum_{z}^{Z}((OPCOSTP_z * \sum_{j}^{J}\sum_{lg2}^{LG2} FTJT\_LG_{j,lg2,z} * DJKL\_LG_{j,lg2}) + (OPCOSTP_z * \sum_{lg2}^{LG2}\sum_{n}^{N} FTLT_{lg2,n,z} * DLMN_{lg2,n})) \tag{5.6}$$

The values of operating costs factors for each transportation mode were obtained from studies by Oo et al. (2012) and Blok et al., (1995). This costs might include the salaries and wages, fuels, maintenances, and etc., while the exact values in \$ per tonne per km are much depending on the types and densities of the transported products. Operating costs for solid transportation using truck, train, and barge were calculating for return trips, while for liquid and gas transportation through the pipeline were not. Further, formulations (5.7) till (5.11) detail about the loads for transportations.

$$\sum_t FTFT_{g,h,t} = FTF_{g,h} \qquad \forall_{g,h} \tag{5.7}$$

$$\sum_t FTHT_{h,j,t} = \sum_i^I FTH_{h,i,j} \qquad \forall_{h,j} \tag{5.8}$$

$$\sum_t FTJT\_S_{s1.s2.t} = \sum_k^K FTJ\_S_{s1,k,s2} \qquad \forall_{s1,s2} \tag{5.9}$$

$$\sum_z FTJT\_LG_{lg1.lg2.z} = \sum_k^K FTJ\_LG_{lg1,k,lg2} \qquad \forall_{lg1,lg2} \tag{5.10}$$

$$\sum_z FTLT_{lg2,n,z} = \sum_m^M FTL_{lg2.m.n} \qquad \forall_{lg2,n} \tag{5.11}$$

Production cost and emission treatment cost were also included in the model, described mathematically by (5.12) till (5.23). The production cost was the result of multiplication between flowrate and production cost factor. Production cost factor was the cost in \$ to produce one unit capacity of product. Approximation of values for these factors were done in every processing unit in the processing facilities because they were difficult to be obtained in exact values. The costs for treating emissions from transportation and production activities in the supply chain have indicated that the environmental performances were considered simultaneously. It used \$40 per tonne of CO_2 equivalent for emission cost as per previous model. Formulations (5.16) till (5.23) represented the mass balances for the emissions that were written in tonne CO_2 equivalent per year.

$$Production\ cost = \left(\sum_h^H \sum_i^I FPH_{h,i} * PROCH_{h,i}\right) + \left(\sum_i^I \sum_j^J \sum_k^K FPJ_{i,j,k} * PROCJ_{i,j,k}\right) + \left(\sum_k^K \sum_{s2}^{S2} \sum_m^M FPL\_S_{k,s2,m} * PROCL\_S_{k,s2,m}\right) + \left(\sum_{lg2}^{LG2} \sum_m^M FPL\_LG_{k,lg2,m} * PROCL\_LG_{k,lg2,m}\right) + \left(\sum_m^M \sum_n^N \sum_o^O FPN_{m,n,o} * PROCN_{m,n,o}\right) \tag{5.12}$$

$$Emission\ treatment\ cost = emission\ treatment\ cost\ from\ production + emission\ treatment\ cost\ from\ transportation \tag{5.13}$$

$$Emission\ treatment\ cost\ from\ production = \left[\left(\sum_h^H \sum_i^I FEVH_{h,i}\right) + \left(\sum_i^I \sum_j^J \sum_k^K FEVJ_{i,j,k}\right) + \left(\sum_k^K \sum_{s2}^{S2} \sum_m^M FEVL\_S_{k,s2,m}\right) + \left(\sum_{lg2}^{LG2} \sum_m^M FEVL\_LG_{k,lg2,m}\right) + \left(\sum_m^M \sum_n^N \sum_o^O FEVN_{m,n,o}\right)\right] * ET\_cost \tag{5.14}$$

$$Emission\ treatment\ cost\ from\ transportation = [(\sum_g^G \sum_h^H \sum_t^T FTFTE_{g,h,t}) + (\sum_h^H \sum_j^J \sum_t^T FTHTE_{h,j,t}) + (\sum_j^J \sum_{s2}^{S2} \sum_t^T FTJTE\_S_{j,s2,t})] * ET\_cost \qquad (5.15)$$

$$FEVH_{h,i} = FPH_{h,i} * ENVH_{h,i} \qquad \forall_{h,i} \qquad (5.16)$$

$$FEVJ_{i,j,k} = FPJ_{i,j,k} * ENVJ_{i,j,k} \qquad \forall_{i,j,k} \qquad (5.17)$$

$$FEVL\_S_{k,s2,m} = FPL\_S_{k,s2,m} * ENVL\_S_{k,s2,m} \qquad \forall_{k,s2,m} \qquad (5.18)$$

$$FEVL\_LG_{k,lg2,m} = FPL\_LG_{k,lg2,m} * ENVL\_LG_{k,lg2,m} \qquad \forall_{k,lg2,m} \qquad (5.19)$$

$$FEVN_{m,n,o} = FPN_{m,n,o} * ENVN_{m,n,o} \qquad \forall_{m.n.o} \qquad (5.20)$$

$$FTFTE_{g,h,t} = FTFT_{g,h,t} * EMFAC_t * DGH_{g,h} \qquad \forall_{g,h,t} \qquad (5.21)$$

$$FTHTE_{h,j,t} = FTHT_{h,j,t} * EMFAC_t * DHIJ_{h,j} \qquad \forall_{h,j,t} \qquad (5.22)$$

$$FTJTE\_S_{j,s2,t} = FTJT\_S_{j,s2,t} * EMFAC_t * DJKL\_S_{j,s2} \qquad \forall_{j,s2,t} \qquad (5.23)$$

The amount of EFB feedstocks at location *g* must be not exceeding their total availability. This has considered the leftovers of EFBs in the fields. In addition, the demands for each of the products *p* that were produced must be met. These have created the following constraints;

$$\sum_g^G F_g \leq Biomass\ Availability \qquad (5.24)$$

$$Five\ percent\ of\ World\ Demands \geq Q_p \geq Bioproduct's\ Demand \qquad \forall_p \qquad (5.25)$$

The other mass balances were represented by (5.26) till (5.40) which comprise an inequality and equalities. Multiplications of continuous and discrete (binary) variables for (5.27), (5.29), (5.31), (5.32), and (5.41) till (5.45) have caused the model to be MINLP, as according to the definition about MINLP by Grossmann and Trespalacios (2014). High computational time is the typical issue with this type of programming. Methods for solving MINLP model have been reported by Grossmann (1999) that included branch and bound method, generalized benders decomposition, outer-approximation, LP/NLP based branch and bound, and extended cutting plane method. For this study however, it used the optimization solver called as Branch-And-Reduce Optimization Navigator (BARON) that is available in GAMS for solving the formulations.

$$\sum_{h}^{H} FTF_{g,h} \leq F_g \qquad \forall_{g} \tag{5.26}$$

$$\sum_{g}^{G} FTF_{g,h} * CONVH_{h,i} * Y1_{h,i} = FPH_{h,i} \qquad \forall_{h,i} \tag{5.27}$$

$$FPH_{h,i} = \sum_{j}^{J} FTH_{h,i,j} + FSH_{h,i} \qquad \forall_{h,i} \tag{5.28}$$

$$\sum_{h}^{H} FTH_{h,i,j} * CONVJ_{i,j,k} * Y2_{i,j,k} = FPJ_{i,j,k} \qquad \forall_{i,j,k} \tag{5.29}$$

$$\sum_{i}^{I} FPJ_{i,j,k} = FSJ_{j,k} + \sum_{s2}^{S2} FTJ\_S_{j,k,s2} + \sum_{lg2}^{LG2} FTJ\_LG_{j,k,lg2} \qquad \forall_{j,k} \tag{5.30}$$

$$\sum_{j}^{J} FTJ\_S_{j,k,s2} * CONVL\_S_{k,s2,m} * Y3a_{k,s2,m} = FPL\_S_{k,s2,m} \qquad \forall_{k,s2,m} \tag{5.31}$$

$$\sum_{j}^{J} FTJ\_LG_{j,k,lg2} * CONVL\_LG_{k,lg2,m} * Y3b_{k,lg2,m} = FPL\_LG_{k,lg2,m} \qquad \forall_{k,lg2,m} \tag{5.32}$$

$$\sum_{k}^{K} FPL\_S_{k,s2,m} = FSL\_S_{s2,m} \qquad \forall_{s2,m} \tag{5.33}$$

$$\sum_{k}^{K} FPL\_LG_{k,lg2,m} = FSL\_LG_{lg2,m} + \sum_{n}^{N} FTL_{lg2,m,n} \qquad \forall_{lg2,m} \tag{5.34}$$

$$\sum_{lg2}^{LG2} FTL_{lg2,m,n} * CONVN_{m,n,o} = FPN_{m,n,o} \qquad \forall_{m,n,o} \tag{5.35}$$

$$\sum_{m}^{M} FPN_{m,n,o} = FSN_{n,o} \qquad \forall_{n,o} \tag{5.36}$$

$$\sum_{h}^{H} FSH_{h,i} = Q_i \qquad \forall_{i} \tag{5.37}$$

$$\sum_{j}^{J} FSJ_{j,k} = Q_k \qquad \forall_{k} \tag{5.38}$$

$$\sum_{s2}^{S2} FSL\_S_{s2,m} + \sum_{lg2}^{LG2} FSL\_LG_{lg2,m} = Q_m \qquad \forall_{m} \tag{5.39}$$

$$\sum_{n}^{N} FSN_{n,o} = Q_o \qquad \forall_{o} \tag{5.40}$$

$$FTFT_{g,h,t} \leq TMAXC_t * YGH_{g,h,t} * X1_t \qquad \forall_{g,h} \tag{5.41}$$

$$FTHT_{h,j,t} \leq TMAXC_t * YHJ_{h,j,t} * X2_t \qquad \forall_{h,j} \tag{5.42}$$

$$FTJT\_S_{s1,s2,t} \leq TMAXC_t * YJL\_S_{s1,s2,t} * X3_t \qquad \forall_{s1,s2} \tag{5.43}$$

$$FTJT\_LG_{lg1,lg2,z} \leq PMAXC_t * YJL\_LG_{lg1,lg2,z} * ZZ1_z \qquad \forall_{lg1,lg2} \tag{5.44}$$

$$FTLT_{lg2,n,z} \leq PMAXC_t * YLN_{lg2,n,z} * ZZ2_z \qquad \forall_{lg2,n} \qquad (5.45)$$

Binary variables will produce either 1 for selection or 0 for not. Formulations (5.46) till (5.50) would be for selecting the transportation mode, while (5.50) till (5.54) would be for processing route.

$$\sum_t YGH_{g,h,t} \leq 1 \qquad \forall_{g,h} \qquad (5.46)$$

$$\sum_t YHJ_{h,j,t} \leq 1 \qquad \forall_{h,j} \qquad (5.47)$$

$$\sum_t YJL\_S_{s1,s2,t} \leq 1 \qquad \forall_{s1,s2} \qquad (5.48)$$

$$\sum_z YJL\_LG_{lg1,lg2,z} \leq 1 \qquad \forall_{lg1,lg2} \qquad (5.49)$$

$$\sum_z YLN_{lg2,n,z} \leq 1 \qquad \forall_{lg2,n} \qquad (5.50)$$

$$\sum_i^I Y1_{h,i} \leq 1 \qquad \forall_h \qquad (5.51)$$

$$\sum_k^K Y2_{i,j,k} \leq 1 \qquad \forall_{i,j} \qquad (5.52)$$

$$\sum_m^M Y3a_{k,s2,m} \leq 1 \qquad \forall_{k,s2} \qquad (5.53)$$

$$\sum_m^M Y3b_{k,lg2,m} \leq 1 \qquad \forall_{k,lg2} \qquad (5.54)$$

It was an intention in this chapter to assign the modes of transportation according to the physical state of the products, which in turn depending closely to the stage of processing. Stage *h* would only produce solid products, stage *j* and *l* would produce solid, liquid and gaseous products, and stage *n* would produce only gaseous products. Therefore, transportation from *g* to *h* would involve only solids, from *h* to *j* would again involve only solids, from *j* to *l* would involve solids, liquids, and gases, from *l* to *n* would involve liquids and gas, and lastly there was no transportation required after *n*. In addition, the model has not considered transportation for every direct-sales product. Formulations (5.55) till (5.56) have represented assignments between transportation mode and products' states based on fractions. In other words, they fractionally distributed transportation capacities according to the products' states.

$$Sum\ of\ X = X1_t + X2_t + X3_t = 1 \qquad \forall_t \qquad (5.55)$$

$$Sum\ of\ Z = ZZ1_z + ZZ2_z = 1 \qquad \forall_z \qquad (5.56)$$

In BARON, it has required to make bound for the selected variables. The following formulations have set the range of capacities for transportation modes at each processing route.

$$0 \leq TMAXC_t \leq 500000 \qquad \forall_t \qquad (5.57)$$

$$0 \leq PMAXC_z \leq 50000 \qquad \forall_z \qquad (5.58)$$

Table 5.2 Description of formulations (5.1) till (5.58)

Formulation	Description
5.1	Objective function
5.2	Equation to calculate total sales of products in $ per year
5.2	Equation to calculate total sales of products in $ per year
5.3	Equation to calculate total EFB's costs in $ per year
5.4	Components in transportation operating costs
5.5	Equation to calculate transportation operating costs for truck, train and barge in $ per year
5.6	Equation to calculate transportation operating costs for pipeline in $ per year
5.7	Total amount of biomass transported from *g* to *h* using transportation *t* in tonne per year
5.8	Total amount of pre-processed products transported from *h* to *j* using transportation *t* in tonne per year
5.9	Total amount of solid intermediate products 1 transported from *s1(j)* to *s2(l)* using transportation *t* in tonne per year
5.10	Total amount of liquid and gaseous intermediate products 1 transported from *lg1(j)* to *lg2(l)* using transportation *z* in tonne per year
5.11	Total amount of intermediate products 2 transported from *lg2(l)* to *n* using transportation *z* in tonne per year
5.12	Equation to calculate production cost in $ per year
5.13	Components in emission treatment costs
5.14	Equation to calculate emission treatment costs from productions in $ per year
5.15	Equation to calculate emission treatment costs from transportations in $ per year
5.16	Equation to calculate emission at *h* to produce *i* in tonne CO_2 equivalent per year
5.17	Equation to calculate emission at *j* to produce *k* in tonne CO_2 equivalent per year

5.18	Equation to calculate emission at *s2(l)* to produce *m* in tonne CO_2 equivalent per year
5.19	Equation to calculate emission at *lg2(l)* to produce *m* in tonne CO_2 equivalent per year
5.20	Equation to calculate emission at *n* to produce *o* in tonne CO_2 equivalent per year
5.21	Equation to calculate emission from transportation between *g* and *h* using transportation mode *t* in tonne CO_2 equivalent per year
5.22	Equation to calculate emission from transportation between *h* and *j* using transportation mode *t* in tonne CO_2 equivalent per year
5.23	Equation to calculate emission from transportation between *j* and *s2(l)* using transportation mode *t* in tonne CO_2 equivalent per year
5.24	Amount of EFB in tonne per year must not exceed the availability
5.25	Range of amounts of produced products in tonne or MWh per year
5.26	Mass balance for EFB sources' storage outlets in tonne per year
5.27	Mass balance for yield of pre-processed feedstocks in tonne per year
5.28	Mass balance for pre-processing facilities outlets in tonne per year
5.29	Mass balance for yield of intermediate products 1 in tonne per year
5.30	Mass balance for main processing facilities outlets in tonne per year
5.31	Mass balance for yield of intermediate products 2 from solid feeds in tonne per year
5.32	Mass balance for yield of intermediate products 2 from solid solution, liquid and gaseous feeds in tonne per year
5.33	Mass balance of *s2(l)* in tonne per year
5.34	Mass balance of *lg2(l)* in tonne per year
5.35	Mass balance for yield of final products in tonne per year
5.36	Mass balance for further processing facilities 2 outlets in tonne per year
5.37	Summation of products at *i* in tonne per year
5.38	Summation of products at *k* in tonne per year
5.39	Summation of products at *m* in tonne per year
5.40	Summation of products at *o* in tonne per year
5.41	Maximum capacity for transportation *t* from *g* to *h* in tonne per year
5.42	Maximum capacity for transportation *t* from *h* to *j* in tonne per year

5.43	Maximum capacity for transportation *t* for solid from *j* to *l* in tonne per year
5.44	Maximum capacity for transportation *z* for liquid and gas from *j* to *l* in tonne per year
5.45	Maximum capacity for transportation *z* for liquid and gas from *l* to *n* in tonne per year
5.46	Integer decision for mode of transportation from *g* to *h*
5.47	Integer decision for mode of transportation from *h* to *j*
5.48	Integer decision for mode of transportation from *s1(j)* to *s2(l)*
5.49	Integer decision for mode of transportation from *lg1(j)* to *lg2(l)*
5.50	Integer decision for mode of transportation from *lg2(l)* to *n*
5.51	Integer decision for best processing route at *h* to produce *i*
5.52	Integer decision for best processing route at *j* to produce *k*
5.53	Integer decision for best processing route at *s2(l)* to produce *m*
5.54	Integer decision for best processing route at *lg2(l)* to produce *m*
5.55	Summation for transporting solid fraction X using transportation t
5.56	Summation for transporting liquid and gas fractions ZZ using transportation *z*
5.57	Upper and lower limits of capacity for transportation *t* at each processing route
5.58	Upper and lower limits of capacity for transportation *z* at each processing route

Table 5.3 Descriptions of terms used in formulations (5.1) till (5.58)

Term	Category	Description
$OPCOSTM_t$	Parameter	Operating cost factor for transportation *t* in \$ per tonne per km
$DGH_{g,h}$	Parameter	Distances for transporting biomass feedstock between *g* to *h* in km
$DHIJ_{h,j}$	Parameter	Distances for transporting pre-processed feedstock between *h* and *j* in km
$DJKL\_S_{j,s2}$	Parameter	Distances for transporting solid intermediate product 1 *k* between *j* and *S2(l)* in km
$OPCOSTP_z$	Parameter	Operating cost factor for pipeline transportation *z* in \$ per tonne per km
$DJKL\_LG_{j,lg2}$	Parameter	Distances for transporting liquid and gaseous intermediate product 1 *k* between *j* and *lg2(l)* in km
$DLMN_{lg2,n}$	Parameter	Distances for intermediate product 2 *m* between *lg2(l)* and *n* in km
$PROCH_{h,i}$	Parameter	Production cost factor at *h* to produce *i* from *g* \$ per tonne
$PROCJ_{i,j,k}$	Parameter	Production cost factor at *j* to produce *k* from *i* \$ per tonne
$PROCL\_S_{k,s2,m}$	Parameter	Production cost factor at *s2(l)* to produce *m* from *k* in \$ per tonne or per MWh
$PROCL\_LG_{k,lg2,m}$	Parameter	Production cost factor at *lg2(l)* to produce *m* from *k* in \$ per tonne or per MWh
$PROCN_{m,n,o}$	Parameter	Production cost factor at *n* to produce *o* from *m* in \$ per tonne
ET_cost	Parameter	Cost of emission treatment in \$ per tonne CO_2 equivalent
$ENVH_{h,i}$	Parameter	Emission factor at *h* in tonne CO_2 equivalent per tonne of *i* produced

$ENVJ_{i,j,k}$	Parameter	Emission factor at *j* in tonne CO_2 equivalent per tonne of *k* produced
$ENVL\_S_{k,s2,m}$	Parameter	Emission factor at *s2(l)* in tonne CO_2 equivalent per tonne of *m* produced
$ENVL\_LG_{k,lg2,m}$	Parameter	Emission factor at *lg2(l)* in tonne CO_2 equivalent per tonne of *m* produced
$ENVN_{m,n,o}$	Parameter	Emission factor at *n* in tonne CO_2 equivalent per tonne of *o* produced
$EMFAC_t$	Parameter	Emission factor of transportation *t* in tonne CO_2 equivalent per tonne per km
$CONVH_{h,i}$	Parameter	Conversion factor at *h* to produce *i* from *g*
$CONVJ_{i,j,k}$	Parameter	Conversion factor at *j* to produce *k* from *i*
$CONVL\_S_{k,s2,m}$	Parameter	Conversion factor at *s2(l)* to produce *m* from *k*
$CONVL\_LG_{k,lg2,m}$	Parameter	Conversion factor at *lg2(l)* to produce *m* from *k*
$CONVN_{m,n,o}$	Parameter	Conversion factor at *n* to produce *o* from *m*
Q_p	Decision variable	Amount of all products *p* stored and ready for sales in tonne or MWh per year
F_g	Decision variable	Amount of biomass at EFB's sources locations in tonne per year
$FTFT_{g,h,t}$	Decision variable	Amount of biomass transported to pre-processing facilities *h* using transportation *t* in tonne per year
$FTHT_{h,j,t}$	Decision variable	Amount of pre-processed feedstocks *i* transported from pre-processing facilities *h* to main processing facilities *j* using transportation *t* in tonne per year
$FTJT\_S_{j,s2,t}$	Decision variable	Amount of solid intermediate products 1 *k* transported from main processing facilities *j* to further processing 1 facilities *s2(l)* using transportation *t* in tonne per year
$FTJT\_S_{s1,s2,t}$	Decision variable	Amount of solid intermediate products 1 *k* transported from main processing facilities *s1(j)* to further processing 1 facilities *s2(l)* using transportation *t* in tonne per year
$FTJT\_LG_{j,lg2,z}$	Variable	Amount of liquid and gaseous intermediate products 1 *k* transported from main processing facilities *j* to further processing 1 facilities *lg2(l)* using pipeline transportation *z* in tonne per year
$FTJT\_LG_{lg1,lg2,z}$	Decision variable	Amount of liquid and gaseous intermediate products 1 *k* transported from main processing facilities *lg1(j)* to further processing 1 facilities *lg2(l)* using pipeline transportation *z* in tonne per year
$FTLT_{lg2,n,z}$	Decision variable	Amount of intermediate products 2 *m* transported from further processing 1 facilities *lg2(l)* to further processing 2 facilities *n* using pipeline transportation *z* in tonne per year
$FTF_{g,h}$	Decision variable	Amount of biomass transported to pre-processing facilities *h* in tonne per year
$FTH_{h,i,j}$	Decision variable	Amount of pre-processed feedstocks *i* transported from pre-processing facilities *h* to main processing facilities *j* in tonne per year
$FTJ\_S_{si,k,s2}$	Decision variable	Amount of solid intermediate products 1 *k* transported from main processing facilities *s1(j)* to further processing 1 facilities *S2(l)* in tonne per year

$FTJ\_S_{j,k,s2}$	Decision variable	Amount of solid intermediate products 1 *k* transported from main processing facilities *j* to further processing 1 facilities *S2(l)* in tonne per year
$FTJ\_LG_{lg1,k,lg2}$	Decision variable	Amount of liquid and gaseous intermediate products 1 *k* transported from main processing facilities *lg1(j)* to further processing 1 facilities *lg2(l)* in tonne per year
$FTJ\_LG_{j,k,lg2}$	Decision variable	Amount of liquid and gaseous intermediate products 1 *k* transported from main processing facilities *j* to further processing 1 facilities *lg2(l)* in tonne per year
$FTL_{lg2.m.n}$	Decision variable	Amount of intermediate products 2 *m* transported from further processing 1 facilities *lg2(l)* to further processing 2 facilities *n* in tonne per year
$FPH_{h,i}$	Decision variable	Amount of pre-processed feedstocks *i* produced from biomass feedstocks *g* through pre-processing facilities *h* in tonne per year
$FPJ_{i,j,k}$	Decision variable	Amount of intermediate product 1 *k* produced from pre-processed feedstocks *i* through main processing facilities *j* in tonne per year
$FPL\_S_{k,s2,m}$	Decision variable	Amount of intermediate products 2 *m* produced from intermediate products 1 *k* through further processing 1 facilities *S2(l)* in tonne per year
$FPL\_LG_{k,lg2,m}$	Decision variable	Amount of intermediate products 2 *m* produced from intermediate products 1 *k* through further processing 1 facilities *lg2(l)* in tonne per year
$FPN_{m,n,o}$	Decision variable	Amount of final products *o* produced from intermediate products 2 *m* through further processing 2 facilities *n* in tonne per year
$FEVH_{h,i}$	Decision variable	Amount of emission at *h* to produce *i* in tonne CO_2 equivalent per year
$FEVJ_{i,j,k}$	Decision variable	Amount of emission at *j* to produce *k* in tonne CO_2 equivalent per year
$FEVL\_S_{k,s2,m}$	Decision variable	Amount of emission at *s2(l)* to produce *m* in tonne CO_2 equivalent per year
$FEVL\_LG_{k,lg2,m}$	Decision variable	Amount of emission at *lg2(l)* to produce *m* in tonne CO_2 equivalent per year
$FEVN_{m,n,o}$	Decision variable	Amount of emission at *n* to produce *o* in tonne CO_2 equivalent per year
$FTFTE_{g,h,t}$	Decision variable	Amount of emission from transportation between *g* and *h* in tonne CO_2 equivalent per year using transportation *t*
$FTHTE_{h,j,t}$	Decision variable	Amount of emission from transportation between *h* and *j* in tonne CO_2 equivalent per year using transportation *t*
$FTJTE\_S_{j,s2,t}$	Decision variable	Amount of emission from transportation between *j* and *s2(l)* in tonne CO_2 equivalent per year using transportation *t*

$Y1_{h,i}$	Binary variable	Binary variable for best production route from *g* to *i* through *h*
$FSH_{h,i}$	Decision variable	Amount of pre-processed feedstocks *i* produced from pre-processing facilities *h* to be sold directly in tonne per year
$Y2_{i,j,k}$	Binary variable	Binary variable for best production route from *i* to *k* through *j*
$FSJ_{j,k}$	Decision variable	Amount of intermediate products 1 *k* produced from main processing facilities *j* to be sold directly in tonne per year
$Y3a_{k,s2,m}$	Binary variable	Binary variable for best production route from *k* to *m* through *s2(l)*
$Y3b_{k,lg2,m}$	Binary variable	Binary variable for best production route from *k* to *m* through *lg2(l)*
$FSL\_S_{s2,m}$	Decision variable	Amount of intermediate products 2 *m* produced from intermediate products 1 *k* through further processing 1 facilities *s2(l)* to be sold directly in tonne per year
$FSL\_LG_{lg2,m}$	Decision variable	Amount of intermediate products 2 *m* produced from intermediate products 1 *k* through further processing 1 facilities *lg2(l)* to be sold directly in tonne per year
$FSN_{n,o}$	Decision variable	Amount of final products *o* produced from intermediate products 2 *m* through further processing 2 facilities *n* to be sold in tonne per year
Q_i	Decision variable	Amount of pre-processed feedstocks stored and ready for sales in tonne per year
Q_k	Decision variable	Amount of intermediate products 1 stored and ready for sales in tonne per year
Q_m	Decision variable	Amount of intermediate products 2 stored and ready for sales in tonne per year
Q_o	Decision variable	Amount of intermediate products 2 stored and ready for sales in tonne per year
$TMAXC_t$	Variable	Maximum capacity in tonne per year for transportation *t* at each processing route
$YGH_{g,h,t}$	Binary variable	Binary variable for best transportation *t* from *g* to *h*
$X1_t$	Binary variable	Transportation of solid fraction from *g* to *h*
$YHJ_{h,j,t}$	Binary variable	Binary variable for best transportation *t* from *h* to *j*
$X2_t$	Binary variable	Transportation of solid fraction from *h* to *j*

$YJL\_S_{s1,s2,t}$	Binary variable	Binary variable for best transportation *t* from *s1(j)* to *s2(l)*
$X3_t$	Binary variable	Transportation of solid fraction from *j* to *l*
$PMAXC_t$	Variable	Maximum capacity in tonne per year for transportation *z* at each processing route
$YJL\_LG_{lg1,lg2,z}$	Binary variable	Binary variable for best transportation *z* from *lg1(j)* to *lg2(l)*
$ZZ1_z$	Variable	Transportation of liquid and gaseous fractions from *j* to *l*
$YLN_{lg2,n,z}$	Binary variable	Binary variable for best transportation *z* from *lg3(l)* to *n*
$ZZ2_z$	Variable	Transportation of liquid and gaseous fractions from *l* to *n*

5.5 Approximation of Parameters

Parameters such as products' selling prices (Table 4.3), demands (Table 4.4), and availability (Table 4.5) of EFB were the same as in the previous model, while the other parameters were presented here. Table 5.4 till 5.8 records the distances between the four stages of processing facilities as shown in the superstructure so that the model could determine the transportation costs. All of these distances were obtained by using Google Maps. Furthermore, distances from j to l were tabulated according to the products' states. Table 5.9 meanwhile shows operating cost factor and emission factor that have been studied by Oo et al. (2012) and Blok et al., (1995), and McKinnon (2008), respectively, for each of the transportation mode. It was assumed that there was no emission from pipeline transportation.

Table 5.4 Distances for transporting EFB feedstock between g to h in km, ($DGH_{g,h}$)

EFB sources locations, *g*	**Pre-processing facilities, *h***	**Distance (km)**
EFB Collection 1	Aerobic Digestion on site	0
EFB Collection 1	DLF Production	271
EFB Collection 1	Extraction Plant 1	322
EFB Collection 1	Extraction Plant 2	322
EFB Collection 1	Extraction Plant 3	322
EFB Collection 1	Briquetting Plant	271
EFB Collection 1	Pelletization Mill	287
EFB Collection 1	Torrefied Pelletization Mill	208
EFB Collection 1	Alkaline Activation (Activated Carbon) Plant	208
EFB Collection 2	Aerobic Digestion on site	0
EFB Collection 2	DLF Production	165
EFB Collection 2	Extraction Plant 1	230
EFB Collection 2	Extraction Plant 2	230
EFB Collection 2	Extraction Plant 3	230

EFB Collection 2	Briquetting Plant	165
EFB Collection 2	Pelletization Mill	195
EFB Collection 2	Torrefied Pelletization Mill	224
EFB Collection 2	Alkaline Activation (Activated Carbon) Plant	224
EFB Collection 3	Aerobic Digestion on site	0
EFB Collection 3	DLF Production	274
EFB Collection 3	Extraction Plant 1	486
EFB Collection 3	Extraction Plant 2	486
EFB Collection 3	Extraction Plant 3	486
EFB Collection 3	Briquetting Plant	274
EFB Collection 3	Pelletization Mill	289
EFB Collection 3	Torrefied Pelletization Mill	346
EFB Collection 3	Alkaline Activation (Activated Carbon) Plant	346

Table 5.5 Distances for transporting pre-processed feedstock between *h* and *j* in km,
$(DHIJ_{h,j})$

Pre-processing facilities, *h*	**Main processing facilities, *j***	**Distance (km)**
Extraction Plant 1	CMC Production	0
Extraction Plant 1	Acid Hydrolysis 1	546
Extraction Plant 1	Enzymatic Hydrolysis 1	315
Extraction Plant 2	Acid Hydrolysis 2	546
Extraction Plant 2	Enzymatic Hydrolysis 2	315
Extraction Plant 3	Resin Production	386
DLF Production	Bio-composite Production	33
Briquetting Plant	Boiler Combustion	83
Pelletization Mill	Boiler Combustion	88
Pelletization Mill	Gasification	17
Pelletization Mill	Fast Pyrolysis	0
Pelletization Mill	Slow Pyrolysis	345
Torrefied Pelletization Mill	Boiler Combustion	23
Torrefied Pelletization Mill	Gasification	78
Torrefied Pelletization Mill	Fast Pyrolysis	86

Table 5.6 Distances for transporting solid intermediate products 1 between *j* and *s2(l)* in km,
$(DJKL\_S_{j,s2})$

Main processing facilities, *j*	**Further processing 1 facilities, *s2(l)***	**Distance (km)**
Acid Hydrolysis 2	Xylitol Production	0
Acid Hydrolysis 1	Anaerobic Digestion Plant	338
Enzymatic Hydrolysis 1	Anaerobic Digestion Plant	37
Enzymatic Hydrolysis 2	Xylitol Production	379

Table 5.7 Distances for transporting liquid and gaseous intermediate products 1 between *j* and *lg2(l)* in km,
$(DJKL\_LG_{j,lg2})$

Main processing facilities, *j*	**Further processing 1 facilities, *lg2(l)***	**Distance (km)**
Boiler combustion	Power production	0
Boiler combustion	MP Steam production	0
Boiler combustion	LP steam production	0
Acid hydrolysis (1 and 2)	Fermentation plant (1 and 2)	327
Enzymatic hydrolysis (1 and 2)	Fermentation plant (1 and 2)	65
Gasification	Separation plant	0
Gasification	Methanol production	404

Gasification	FTL production (1 and 2)	19
Fast pyrolysis	Bio-oil upgrading (1 and 2)	94
Fast pyrolysis	Steam Reforming Plant	0

Table 5.8 Distances for intermediate product 2 between $lg2(l)$ and n in km, $(DLMN_{lg2,n})$

Further processing 1 facilities, *lg2(l)*	**Further processing 2 facilities, *n***	**Distance (km)**
Steam Reforming Plant	Ammonia Production	361
Separation Plant	Ammonia Production	367
Methanol Production	Formaldehyde Production	686
Fermentation Plant (1 and 2)	Bio-ethylene	316

Table 5.9 Operating cost factor and emission factor for transportation mode

Transportation mode	**Operating cost factor ($ per tonne per km)**	**Emission factor (tonne CO$_2$ equivalent per tonne per km)**
Truck	0.1641	0.000062
Train	0.0333	0.000022
Barge	0.0136	0.000015
Pipeline	0.0500	-

The production cost factors, conversion factors and emission factors from productions were tabulated accordingly in Table 5.10 till 5.24. Particularly at *l*, depending to the states of products from j, separate tables have shown the related parameters clearly. Approximation of parameters were done due to difficulties for obtaining real data for this model. The parameters were sufficient to prove model's practicality and they were independent of scales, configurations, feedstocks' conditions, and etc.

Table 5.10 Approximated production cost factor at *h* in $ per tonne

Biomass type, *g*	**Pre-Processing, *h***	**Pre-processed product, *i***	**$/tonne**	**Reference**
Blended EFBs	DLF Production	Dry Long Fiber	85	www.hempfarm.com
Blended EFBs	Aerobic Digestion	Bio-compost	10	Fabian et al. (1993)
Blended EFBs	Alkaline Activation	Activated Carbon	144	Lima et al. (2008)
Blended EFBs	Extraction 1	Cellulose	125	Murillo-Alvarado et al. (2013)
Blended EFBs	Extraction 2	Hemicellulose	130	Murillo-Alvarado et al. (2013)
Blended EFBs	Extraction 3	Lignin	135	Murillo-Alvarado et al. (2013)
Blended EFBs	Briquetting	Briquette	50	Kanna (2010)
Blended EFBs	Pelletization	Pellet	60	PPD Technologies Inc. (2011)

Blended EFBs	Torrefied Pelletization	Torrefied Pellet	70	PPD Technologies Inc. (2011)

Table 5.11 Approximated conversion factor at *h*

Biomass type, *g*	**Pre-Processing, *h***	**Pre-processed product, *i***	**Conversion factor**	**Reference**
Blended EFBs	DLF Production	Dry Long Fiber	0.37	Ng and Ng (2013)
Blended EFBs	Aerobic Digestion	Bio-compost	0.95	Hubbe et al. (2010)
Blended EFBs	Alkaline Activation	Activated Carbon	0.50	Kaghazchi et al. (2006)
Blended EFBs	Extraction 1	Cellulose	0.70	Assumed value based on hemicellulose and lignin conversion factor
Blended EFBs	Extraction 2	Hemicellulose	0.15	www.ipst.gatech.edu
Blended EFBs	Extraction 3	Lignin	0.15	www.purelignin.com
Blended EFBs	Briquetting	Briquette	0.38	Ng and Ng (2013)
Blended EFBs	Pelletization	Pellet	0.38	Ng and Ng (2013)
Blended EFBs	Torrefied Pelletization	Torrefied Pellet	0.38	Ng and Ng (2013)

Table 5.12 Approximated CO_2 emission factor at *h*

Biomass type, *g*	**Pre-Processing, *h***	**Pre-processed Product, *i***	**CO_2 emission factor (tonne CO_2 equivalent/tonne of product produced)**	**Reference**
Blended EFBs	DLF Production	Dry Long Fiber	0.0041	www.oecotextiles.wordpress.com
Blended EFBs	Aerobic Digestion	Bio-compost	0.0200	www.epa.gov
Blended EFBs	Alkaline Activation	Activated Carbon	0.0176	www.omnipure.com
Blended EFBs	Extraction 1	Cellulose	0.0590	Murillo-Alvarado et al. (2013)
Blended EFBs	Extraction 2	Hemicellulose	0.0650	Murillo-Alvarado et al. (2013)
Blended EFBs	Extraction 3	Lignin	0.0620	Assumed value based on values for cellulose and hemicellulose
Blended EFBs	Briquetting	Briquette	0.0500	Assumed value
Blended EFBs	Pelletization	Pellet	0.0500	Assumed value
Blended EFBs	Torrefied Pelletization	Torrefied Pellet	0.0805	Kaliyan et al. (2014)

Table 5.13 Approximated production cost factor at *j* in $ per tonne

Pre-processed feedstock, *i*	**Main processing, *j***	**Intermediate product 1, *k***	**$/tonne**	**Reference**
Dry Long Fiber	Bio-composite Production	Bio-composite	107.0	www.eria.org
Cellulose	CMC Production	CMC	2500.0	www.trade.ec.europa.eu
Cellulose	Acid Hydrolysis 1	Glucose	73.4	Murillo-Alvarado et al. (2013)
Cellulose	Enzymatic Hydrolysis 1	Glucose	85.7	Murillo-Alvarado et al. (2013)
Hemicellulose	Acid Hydrolysis 2	Xylose	168.7	Murillo-Alvarado et al. (2013)

Hemicellulose	Enzymatic Hydrolysis 2	Xylose	83.1	Murillo-Alvarado et al. (2013)
Lignin	Resin Production	Bio-resin	1900.0	Chiarakorn et al. (2013)
Briquette	Boiler Combustion	HP Steam	20.7	www1.eere.energy.gov
Pellet	Boiler Combustion	HP Steam	20.7	www1.eere.energy.gov
Pellet	Gasification	Bio-syngas	300.0	Assumed value based on 50% of Bio-syngas price
Pellet	Fast pyrolysis	Bio-oil	1003	Thorp (2010)
Pellet	Slow pyrolysis	Bio-char	111.5	www.irena.org
Torrefied Pellet	Boiler Combustion	HP Steam	20.7	www1.eere.energy.gov
Torrefied Pellet	Gasification	Bio-syngas	300.0	Assumed value based on 50% of Bio-syngas price
Torrefied Pellet	Fast pyrolysis	Bio-oil	1003	Thorp (2010)

Table 5.14 Approximated conversion factor at *j*

Pre-processed feedstock, *i*	**Main processing, *j***	**Intermediate product 1, *k***	**Conversion factor**	**Reference**
Dry Long Fiber	Bio-composite Production	Bio-composite	0.75	Karbstein et al. (2013)
Cellulose	CMC Production	CMC	0.86	Saputra et al. (2014)
Cellulose	Acid Hydrolysis 1	Glucose	0.37	Murillo-Alvarado et al. (2013)
Cellulose	Enzymatic Hydrolysis 1	Glucose	0.47	Murillo-Alvarado et al. (2013)
Hemicellulose	Acid Hydrolysis 2	Xylose	0.91	Murillo-Alvarado et al. (2013)
Hemicellulose	Enzymatic Hydrolysis 2	Xylose	0.88	Murillo-Alvarado et al. (2013)
Lignin	Resin Production	Bio-resin	0.95	Yin et al. (2012)
Briquette	Boiler Combustion	HP Steam	0.20	Searcy and Flynn (2009)
Pellet	Boiler Combustion	HP Steam	0.25	Searcy and Flynn (2009)
Pellet	Gasification	Bio-syngas	0.70	Boerrigter and Drift (2005)
Pellet	Fast pyrolysis	Bio-oil	0.60	Zhang et al. (2013)
Pellet	Slow pyrolysis	Bio-char	0.50	www.biocharfarms.org
Torrefied Pellet	Boiler Combustion	HP Steam	0.30	Searcy and Flynn (2009)
Torrefied Pellet	Gasification	Bio-syngas	0.80	Boerrigter and Drift (2005)
Torrefied Pellet	Fast pyrolysis	Bio-oil	0.60	Zhang et al. (2013)

Table 5.15 Approximated CO$_2$ emission factor at *j*

Pre-processed feedstock, *i*	**Main processing, *j***	**Intermediate product 1, *k***	**CO$_2$ emission factor (tonne CO$_2$ equivalent/tonne of product produced)**	**Reference**
Dry Long Fiber	Bio-composite Production	Bio-composite	7.481	www.winrigo.com
Cellulose	CMC Production	CMC	0.097	Assumed value
Cellulose	Acid Hydrolysis 1	Glucose	0.097	Murillo-Alvarado et al. (2013)
Cellulose	Enzymatic Hydrolysis 1	Glucose	0.085	Murillo-Alvarado et al. (2013)
Hemicellulose	Acid Hydrolysis 2	Xylose	0.075	Murillo-Alvarado et al. (2013)

Hemicellulose	Enzymatic Hydrolysis 2	Xylose	0.082	Murillo-Alvarado et al. (2013)
Lignin	Resin Production	Bio-resin	2.500	www.netcomposites.com
Briquette	Boiler Combustion	HP Steam	0.750	www.sarawakenergy.com.my
Pellet	Boiler Combustion	HP Steam	0.750	Assumed value
Pellet	Gasification	Bio-syngas	0.680	Basu (2013)
Pellet	Fast pyrolysis	Bio-oil	0.580	Zhang et al. (2013)
Pellet	Slow pyrolysis	Bio-char	0.580	Zhang et al. (2013)
Torrefied Pellet	Boiler Combustion	HP Steam	0.750	Assumed value
Torrefied Pellet	Gasification	Bio-syngas	0.680	Basu (2013)
Torrefied Pellet	Fast pyrolysis	Bio-oil	0.580	Zhang et al. (2013)

Table 5.16 Approximated production cost factor at *s2(l)* in \$ per tonne

Intermediate product 1, *k*	**Further processing 1, *s2(l)***	**Intermediate product 2, *m***	**\$/tonne**	**Reference**
Glucose	Anaerobic Digestion	Bio-gas	199.0	Assumed value for 50% less of the bio-gas price
Xylose	Anaerobic Digestion	Bio-gas	199.0	Assumed value for 50% less of the bio-gas price
Xylose	Xylitol Production	Xylitol	2100.0	Assumed value for 50% less of the xylitol price

Table 5.17 Approximated production cost factor at *lg2(l)* in \$ per tonne or per MWh

Intermediate product 1, *k*	**Further processing 1, *lg2(l)***	**Intermediate product 2, *m***	**\$/tonne or MWh**	**Reference**
Bio-oil	Steam Reforming	Bio-hydrogen	455.0	Sarkar and Kumar et al. (2010)
Bio-oil	Bio-oil Upgrading 1	Bio-gasoline	1089.0	Wright and Brown (2011)
Bio-oil	Bio-oil Upgrading 2	Bio-diesel	918.0	Wright and Brown (2011)
Glucose	Fermentation 1	Bio-ethanol	98.2	Murillo-Alvarado et al. (2013)
Xylose	Fermentation 2	Bio-ethanol	98.2	Murillo-Alvarado et al. (2013)
HP Steam	Power Production	Electricity	58.9/MWh	Searcy and Flynn (2009)
HP Steam	Power Production	MP Steam	12.0	Assumed valued based on the steam price
HP Steam	Power Production	LP Steam	7.0	Assumed valued based on the steam price
Bio-syngas	Methanol Production	Bio-methanol	83.6	Murillo-Alvarado et al. (2013)
Bio-syngas	Separation	Bio-hydrogen	112	Schubert (2013)
Bio-syngas	FTL Productions 2	Bio-diesel	167.3	Murillo-Alvarado et al. (2013)
Bio-syngas	FTL Productions 1	Bio-gasoline	519.8	Wright and Brown (2011)

Table 5.18 Approximated conversion factor at *s2(l)*

Intermediate product 1, *k*	**Further processing 1, *s2(l)***	**Intermediate product 2, *m***	**Conversion factor**	**Reference**
Glucose	Anaerobic Digestion	Bio-gas	0.70	Hubbe et al. (2010)
Xylose	Anaerobic Digestion	Bio-gas	0.70	Hubbe et al. (2010)

Xylose	Xylitol Production	Xylitol	0.70	Prakasham et al. (2009)

Table 5.19 Approximated conversion factor at *lg2(l)*

Intermediate product 1, *k*	**Further processing 1, *lg2(l)***	**Intermediate product 2, *m***	**Conversion factor**	**Reference**
Bio-oil	Steam Reforming	Bio-hydrogen	0.84	Dillich (2013)
Bio-oil	Bio-oil Upgrading 1	Bio-gasoline	0.40	Kim et al. (2011)
Bio-oil	Bio-oil Upgrading 2	Bio-diesel	0.20	Kim et al. (2011)
Glucose	Fermentation 1	Bio-ethanol	0.33	Murillo-Alvarado et al. (2013)
Xylose	Fermentation 2	Bio-ethanol	0.33	Murillo-Alvarado et al. (2013)
HP Steam	Power Production	Electricity	0.30 MWh/tonne of steam	www.turbinesinfo.com
HP Steam	Power Production	MP Steam	0.35	Ng and Ng (2013)
HP Steam	Power Production	LP Steam	0.35	Ng and Ng (2013)
Bio-syngas	Methanol Production	Bio-methanol	0.41	Murillo-Alvarado et al. (2013)
Bio-syngas	Separation	Bio-hydrogen	0.46	Murillo-Alvarado et al. (2013)
Bio-syngas	FTL Productions 2	Bio-diesel	0.71	Boerrigter and Drift (2005)
Bio-syngas	FTL Productions 1	Bio-gasoline	0.29	Assumed value from bio-diesel conversion factor

Table 5.20 Approximated CO_2 emission factor at *s2(l)*

Intermediate product 1, *k*	**Further processing 1, *s2(l)***	**Intermediate product 2, *m***	**CO_2 emission factor (tonne CO_2 equivalent/tonne of product produced)**	**Reference**
Glucose	Anaerobic Digestion	Bio-gas	0.250	Whiting & Azapagic, (2014)
Xylose	Anaerobic Digestion	Bio-gas	0.250	Whiting & Azapagic, (2014)
Xylose	Xylitol Production	Xylitol	0.082	Assumed value based on value of xylose

Table 5.21 Approximated CO_2 emission factor at *lg2(l)*

Intermediate product 1, *k*	**Further processing 1, *lg2(l)***	**Intermediate product 2, *m***	**CO_2 emission factor (tonne CO_2 equivalent/tonne of product produced)**	**Reference**
Bio-oil	Steam Reforming	Bio-hydrogen	16.930	Zhang et al. (2013)
Bio-oil	Bio-oil Upgrading 1	Bio-gasoline	13.000	Zhang et al. (2013)
Bio-oil	Bio-oil Upgrading 2	Bio-diesel	13.000	Zhang et al. (2013)
Glucose	Fermentation 1	Bio-ethanol	0.098	Murillo-Alvarado et al. (2013)

Xylose	Fermentation 2	Bio-ethanol	0.098	Murillo-Alvarado et al. (2013)
HP Steam	Power Production	Electricity	0.050	Assumed value
HP Steam	Power Production	MP Steam	0.050	Assumed value
HP Steam	Power Production	LP Steam	0.050	Assumed value
Bio-syngas	Methanol Production	Bio-methanol	0.083	Murillo-Alvarado et al. (2013)
Bio-syngas	Separation	Bio-hydrogen	0.090	Murillo-Alvarado et al. (2013)
Bio-syngas	FTL Productions 2	Bio-diesel	0.067	Murillo-Alvarado et al. (2013)
Bio-syngas	FTL Productions 1	Bio-gasoline	0.639	Murillo-Alvarado et al. (2013)

Table 5.22 Approximated production cost factor at *n* in $ per tonne

Intermediate product 2, *m*	**Further processing 2, *n***	**Final product, *p***	**$/tonne**	**Reference**
Bio-hydrogen	Ammonia Production	Ammonia	377	www.hydrogen.energy.gov
Bio-methanol	Formaldehyde Production	Formaldehyde	232	www.icis.com
Bio-ethanol	Bio-ethylene Production	Bio-ethylene	1200	www.irena.org

Table 5.23 Approximated conversion factor at *n*

Intermediate product 2, *m*	**Further processing 2, *n***	**Final product, *p***	**Conversion factor**	**Reference**
Bio-hydrogen	Ammonia Production	Ammonia	0.80	www.hydrogen.energy.gov
Bio-methanol	Formaldehyde Production	Formaldehyde	0.97	Chu et al. (1997)
Bio-ethanol	Bio-ethylene Production	Bio-ethylene	0.99	www.irena.org

Table 5.24 Approximated CO_2 emission factor at *n*

Intermediate product 2, *m*	**Further processing 2, *n***	**Final product, *p***	**CO_2 emission factor (tonne CO_2 equivalent/tonne of product produced)**	**Reference**
Bio-hydrogen	Ammonia Production	Ammonia	1.694	Jubb et al. (2006)
Bio-methanol	Formaldehyde Production	Formaldehyde	0.083	Assumed value
Bio-ethanol	Bio-ethylene Production	Bio-ethylene	1.400	www.irena.org

5.6 Results and Discussions

Optimization formulations as shown above were performed in GAMS Rev. 149 by using BARON Rev 8.1.1 as a solver in AMD A10-4600M APU processor. With the given parameters, the optimal value of overall net profit was obtained to be $ 1,561,106,613 per year that could be gained by single ownership for all facilities in the supply chain. The model's statistics have shown that it has 66 blocks of equations, 55 blocks of variables, 6540 single equations, 10900 single variables and took 4 minutes to solve. Figure 5.4a shows the superstructure with processing routes (red dash arrows) and processing units (red dash lines) that would be eliminated prior optimization, while Figure 5.4b shows the optimal one.

The superstructure optimization has eliminated processing routes and units. EFBs from collection point 1 (Johore) would be sent for pre-processing to all facilities except extraction 3 at the amounts of 3147894.737 tonnes per year. EFBs from collection point 2 (Pahang) would be utilized at the amounts of 2717543.860 tonnes per year and been sent to DLF production, extraction 1, extraction 2, extraction 3, pelletization and torrefied pelletization. EFBs from collection point 3 (Perak) would be consumed at the amounts of 2447368.421 tonnes per year in DLF production, extraction 1, extraction 2, pelletization and torrefied pelletization. If the supplies of the EFBs at a single collection point were not sufficient, homogenous blending by using EFBs from other collection points would be done. To produce all the products, 8,373235.36 tonnes per year of EFBs would be utilized at the cost of $ 6 per tonne. Table 5.25 shows optimal production levels of all products after optimal selections have been implemented.

Table 5.25 Optimal production level of products

Product	Production (tonne per year or MWh per year)
DLF	543314.563
Bio-compost	20000.000
Activated carbon	95000.000
Cellulose	290500.000
Hemicellulose	186503.475
Lignin	30000.000
Briquette	186000.000
Pellet	59770.263
Torrefied pellet	129749.841
Bio-composite	0.920
CMC	20000.000
Glucose	277200.544
Xylose	29708.518
Bio-resin	10000.000
HP steam	62667.864
Bio-syngas	462000.000

Bio-oil	41587.981
Bio-char	3000.000
Bio-hydrogen	3581.311
Xylitol	0.002
Bio-ethanol	8924.511
Bio-gas	1295.000
Bio-methanol	0.300
Electricity	20.000
MP Steam	0.900
LP Steam	0.450
Bio-ethylene	140.000
Bio-diesel	348.809
Bio-gasoline	143.327
Ammonia	170.000
Formaldehyde	42.000

Based on Figure 5.4a and 5.4b, from *i*, hemicellulose would no longer be sent to acid hydrolysis 2 but only would be consumed at enzymatic hydrolysis 2 to produce xylose. As a result, processing route from hemicellulose to xylose through acid hydrolysis 2 has been eliminated in the optimal superstructure. Briquette and pellet were not sent to boiler combustion. Instead, the boiler combustion has only utilized torrefied pellet for producing HP steam. Fast pyrolysis has only one feed the came from pellet and no longer used torrefied pellet as a feed.

From *k*, processing route from xylose to produce bio-gas through anaerobic digestion has been eliminated. Instead, there was only one and optimal processing route to produce bio-gas through anaerobic digestion which used portions of glucose. Xylose also was no longer became an input to fermentation to produce bio-ethanol. In addition, since all of the produced bio-oil would be sold directly to the customer, related further processing routes and units that should utilize this product were dismissed. Specifically, steam reforming, bio-upgrading 1 and 2 at *l* were removed from the optimal superstructure. Bio-gasoline and bio-diesel were only produced from FTL production 1 and FTL production 2, respectively. Bio-hydrogen was meanwhile generated from bio-syngas through separation.

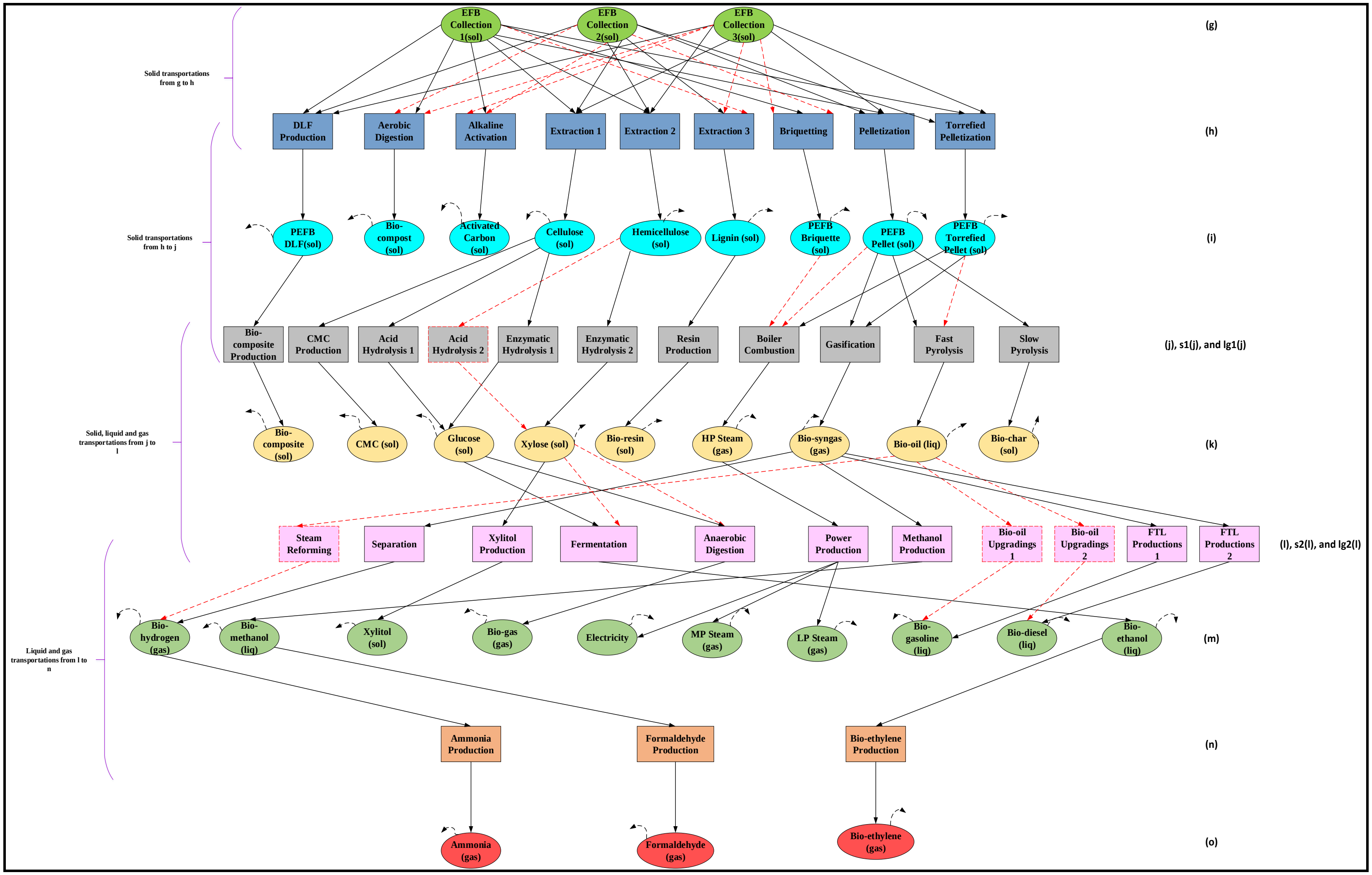

Figure 5.4a Optimization process for processing routes and processing unit

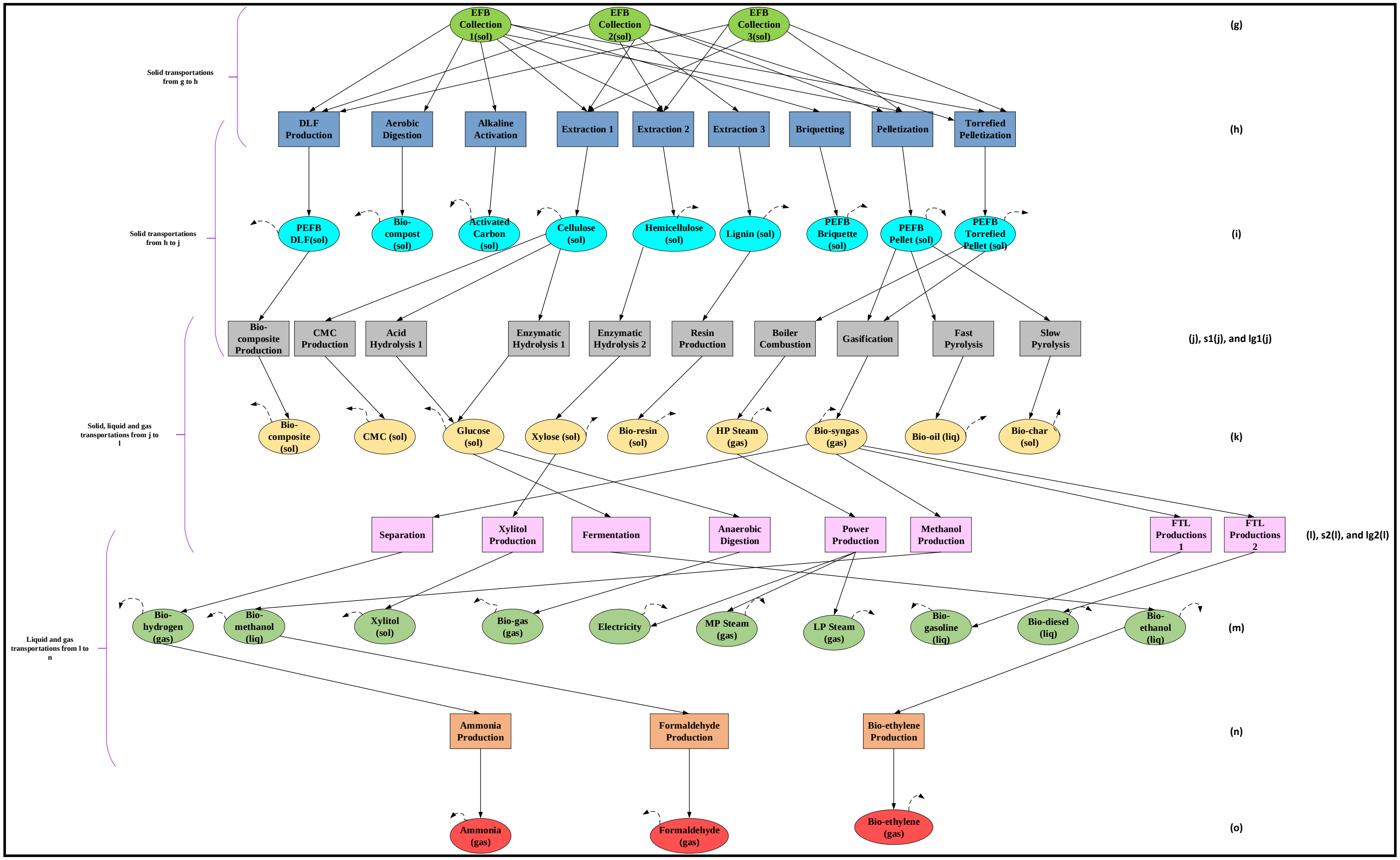

Figure 5.4b Final superstructure of EFB supply chain with optimal processing routes

Optimal results for transportation modes at each processing route and emissions from such transportation activities are tabulated in Table 5.26 till 5.29. Emission values were negligible for transportations that used pipeline and transportations that involved very close distances between two processing facilities. Furthermore, the optimal results have assigned 97.9% of barges' capacities to serve for solid transportations between *g* and *h*, and the remaining capacities for transportations between *h* and *j*. For trains, 84.6% of their capacities have been used for transportations between *h* and *j*, and the remaining for solids transportations between *j* and *l*. For trucks, 86.1% of their capacities were utilized for solids transportations between *g* to *h*, and the remaining capacities were between *h* and *j*. For liquid and gaseous products, 97.2% of pipeline capacities were used for transportations from *j* to *l*, and the balances were assigned from *l* to *n*.

Table 5.26 Optimal results for transportations between EFB collection points, *g* and pre-processing facilities, *h*

EFB sources	**Pre-processing facility**	**Amounts to be transported (tonne per year)**	**Optimal mode of transportation**	**Emission (tonne of CO_2 equivalent per year)**
EFB collection 1	DLF production	489473.684	Barge	1989.711
EFB collection 1	Aerobic digestion	21052.632	Barge	-
EFB collection 1	Alkaline activation	190000.000	Barge	592.800
EFB collection 1	Extraction 1	489473.684	Barge	2364.158
EFB collection 1	Extraction 2	489473.684	Barge	2364.158
EFB collection 1	Briquetting	489473.684	Barge	1989.711
EFB collection 1	Pelletization	489473.684	Barge	2107.184
EFB collection 1	Torrefied pelletization	489473.684	Barge	1527.158
EFB collection 2	DLF production	489473.684	Barge	1211.447
EFB collection 2	Extraction 1	489473.684	Barge	1688.684

EFB collection 2	Extraction 2	489473.684	Barge	1688.684
EFB collection 2	Extraction 3	270175.439	Barge	932.105
EFB collection 2	Pelletization	489473.684	Barge	1431.711
EFB collection 2	Torrefied pelletization	489473.684	Barge	1644.632
EFB collection 3	DLF production	489473.684	Barge	2011.737
EFB collection 3	Extraction 1	489473.684	Barge	3568.263
EFB collection 3	Extraction 2	489473.684	Barge	3568.263
EFB collection 3	Pelletization	489473.684	Barge	2121.868
EFB collection 3	Torrefied pelletization	489473.684	Barge	2540.368

Table 5.27 Optimal results for transportations between pre-processing facilities, *h* and main processing facilities, *j*

Pre-processing facility and product	Main processing facility	Amounts to be transported (tonne per year)	Optimal mode of transportation	Emission (tonne of CO$_2$ equivalent per year)
DLF production and DLF	Bio-composite production	1.227	Train	8.905 x 10^{-4}
Extraction 1 and cellulose	CMC production	23255.814	Truck	-
Extraction 1 and cellulose	Enzymatic hydrolysis 1	422916.436	Train	2930.811
Extraction 1 and cellulose	Acid hydrolysis 1	291222.487	Train	3498.165
Extraction 2 and hemicellulose	Enzymatic hydrolysis 2	33759.683	Train	233.955
Pelletization and pellet	Gasification	422916.436	Train	158.171

Pelletization and pellet	Fast pyrolysis	69313.301	Truck	-
Pelletization and pellet	Slow pyrolysis	6000.000	Barge	31.050
Torrefied pelletization and torrefied pellet	Boiler combustion	209127.960	Train	105.819
Torrefied pelletization and torrefied pellet	Gasification	219122.199	Train	376.014

Table 5.28 Optimal results for transportations between main processing facilities, *j* and further processing 1 facilities, *l* (*s2* and *l2*)

Main processing facility and product	**Further processing 1 facility**	**Amounts to be transported (tonne per year)**	**Optimal mode of transportation**	**Emission (tonne of CO_2 equivalent per year)**
Acid hydrolysis 1 and glucose	Anaerobic digestion	1850.000	Train	13.757
Enzymatic hydrolysis 2 and xylose	Xylitol production	0.003	Train	2.382 x 10^{-5}
Acid hydrolysis 1 and glucose	Fermentation	27472.501	Pipeline	-
Boiler combustion and HP steam	Power production	66.667	Pipeline	-
Boiler combustion and HP steam	Power production for MP steam	2.571	Pipeline	-
Boiler combustion and HP steam	Power production for LP steam	1.286	Pipeline	-
Gasification and bio-syngas	Separation	8247.415	Pipeline	-
Gasification and bio-syngas	Methanol production	106.339	Pipeline	-

Gasification and bio-syngas	FTL Production 1	494.231	Pipeline	-
Gasification and bio-syngas	FTL Production 2	491.280	Pipeline	-

Table 5.29 Optimal results for transportations between further processing 1 facilities, *l* and further processing 2 facilities, *n*

Further processing 1 facility and product	**Further processing 2 facility**	**Amounts to be transported (tonne per year)**	**Optimal mode of transportation**	**Emission (tonne of CO_2 equivalent per year)**
Separation and bio-hydrogen	Ammonia production	212.500	Pipeline	-
Fermentation and bio-ethanol	Bio-ethylene production	141.414	Pipeline	-
Methanol production and bio-methanol	Formaldehyde production	43.299	Pipeline	-

Table 5.30 till 5.33 show the optimal results for productions of every processing facilities with their respective emission levels. Optimal production rate in tonne per year for all products have considered the constraint which it must be at least met the annual demands. In order to know on how much portions of the products need to be sent for further processing, one could find the difference between production rate and amounts to be sold directly to the customers.

Table 5.30 Optimal results for productions at pre-processing facilities, *h*

Processing route	**Production rate (tonnes per year)**	**Amounts to be sold directly (tonnes per year)**	**Emission (tonne of CO_2 equivalent per year)**
Blended EFBs - DLF production - DLF	543315.789	543314.563	2227.595
Blended EFBs - aerobic digestion - bio-compost	20000.000	20000.000	400.000
Blended EFBs - alkaline activation - activated carbon	95000.000	95000.000	1672.000

Blended EFBs - extraction 1 - cellulose	1027894.737	290500.000	60645.789
Blended EFBs - extraction 2 - hemicellulose	220263.158	186503.475	14317.105
Blended EFBs - extraction 3 - lignin	40526.316	30000.000	2512.632
Blended EFBs - briquetting - briquette	186000.000	186000.000	9300.000
Blended EFBs - pelletization - pellet	139108.301	59770.263	27900.000
Blended EFBs - torrefied pelletization - torrefied pellet	558000.000	129749.841	44919.000

Table 5.31 Optimal results for productions at main processing facilities, *j*

Processing route	**Optimal production rate (tonnes per year)**	**Amounts to be sold directly (tonnes per year)**	**Emission (tonne of CO_2 equivalent per year)**
DLF - bio-composite production - bio-composite	0.920	0.920	6.883
Cellulose - CMC production - CMC	20000.000	20000.000	1940.000
Cellulose - acid hydrolysis 1 - glucose	107752.320	78429.819	10451.975
Cellulose - enzymatic hydrolysis 1 - glucose	198770.725	198770.725	16895.512
Hemicellulose - enzymatic hydrolysis 2 - xylose	29708.521	29708.518	2436.099
Lignin - resin production - bio-resin	10000.000	10000.000	25000.000
Torrefied pellet - boiler combustion - HP steam	62738.388	62667.864	47053.791
Pellet -gasification - bio-syngas	296041.505	286702.241	201308.223
Torrefied pellet - gasification - bio-syngas	175297.759	175297.759	119202.476

Pellet - fast pyrolysis - bio-oil	41587.981	41587.981	49181.949
Pellet - slow pyrolysis – bio-char	3000.000	3000.000	1740.000

Table 5.32 Optimal results for productions at further processing 1 facilities, *l* (*s2* and *l2*)

Processing route	**Optimal production rate (tonnes per year)**	**Amounts to be sold directly (tonne or MWh per year)**	**Emission (tonne of CO_2 equivalent per year)**
Xylose - xylitol production - xylitol	0.002	0.002	1.640×10^{-4}
Xylose - anaerobic digestion - bio-gas	1295.000	1295.000	323.750
Xylose - fermentation - bio-ethanol	9065.925	8924.511	888.461
Bio-syngas - separation - bio-hydrogen	3793.811	3581.311	341.443
Bio-syngas - methanol production - methanol	43.599	0.300	3.619
Bio-syngas - FTL production 1 - bio-gasoline	143.327	143.327	91.586
Bio-syngas - FTL production 2 - bio-diesel	348.809	348.809	23.370
HP steam - power production - electricity	20.000	20.000	1.000
HP steam - power production - MP steam	0.900	0.900	0.045
HP steam - power production - LP steam	0.450	0.450	0.023

Table 5.33 Optimal results for productions at further processing 2 facilities, *n*

Processing route	**Optimal production rate (tonnes per year)**	**Amounts to be sold (tonnes per year)**	**Emission (tonne of CO_2 equivalent per year)**
Bio-hydrogen - ammonia production - ammonia	170.000	170.000	287.980

Bio-ethanol - bio-ethylene production - bio-ethylene	140.000	140.000	196.000
Bio-methanol - formaldehyde production - formaldehyde	42.000	42.000	3.486

5.7 Sensitivity Analysis

The optimal results that included the selections of optimal processing routes, transportation modes and decision variables which have been presented are subject to have differences depending on the parameters that were used. Uncertainties in economic and technological factors are among the influential issues in a deterministic modeling. Hence, investigations need to be done to find important parameter that could affect large variations to the optimal results. These kind of investigations are called sensitivity analysis or perturbation analysis, and can be divided into local sensitivity analysis that consider one parameter at a time in a small range, and global sensitivity analysis which perturbs multi-parameters simultaneously over a large range.

Since the developed optimization model has involved NLP, simultaneous considerations for multi-parameters were done to achieve global sensitivity analysis. Even though a myriad of simultaneous perturbations are possible, the sensitivity analysis here have only considered ammonia's selling price, conversion factor and production cost factor for demonstration purposes. The changes in these parameters were carried out by classifying them into three scenarios as shown by Table 5.34. Both original selling price and production cost factor were increased until 50% and the conversion factor was set until 0.95. The overall profits have shown non-linear patterns with the increased values of the three parameters. In pursuit to find the most important parameter for the developed model, more thorough sensitivity analysis might be required.

Table 5.34 Sensitivity analysis for some of parameters related to ammonia

Scenario	**Overall profit**
Original case i) Selling price: $ 745/tonne ii) Production cost factor: $ 377/tonne iii) Conversion factor: 0.8	1,561,106,613
Scenario 1 i) Selling price: $ 819.5/tonne (+10%) ii) Production cost factor: $ 414.7/tonne (+10%)	1,591,266,115

iii) Conversion factor: 0.85	
Scenario 2 iv) Selling price: $ 968.5/tonne (+30%) v) Production cost factor: $ 490.1/tonne (+30%) vi) Conversion factor: 0.90	1,582,494,479
Scenario 3 i) Selling price: $ 1117.5/tonne (+50%) ii) Production cost factor: $ 564.5/tonne (+50%) iii) Conversion factor: 0.95	1,615,100,296

5.8 Conclusion and Future Works

The developed optimization model has extended the previous one by adding integer decision for best processing routes and transportation modes for the multi-products productions from Malaysian’s EFBs in the context of supply chain. The previous superstructure was modified to divide several processing units so that the model could select the optimal ones. It also added the classifications of processing routes and products according to their states whether solid, liquid and gas which would help to determine the best assignments for transportation modes. In addition, environmental considerations have been included in the model in the form of emission treatment costs from both production and transportation activities. Since the model contains approximated parameters due to the issues of availabilities and uncertainties, sensitivity analysis have been done to demonstrate those changes in the objective function. Such parameter approximations were however still sufficient to show the model’s practicality to solve large and complex biomass supply chain like in this one. The single owner of the EFB supply chain could now has a better judgement in prioritizing the prospective manufacturing investments.

For the future works, the model could be further developed by considering stochastic behaviors of the economics and financial planning that are related to the biomass supply chain

Chapter 6

Conclusion and Recommendations for Future Work

In this chapter, overall conclusion is provided as to link conclusions that were made in Chapter 3 till Chapter 5. In addition, recommendations are also presented that could be used for future works.

6.1 Conclusion

Scientific and technological advances have shown intensified outcomes amid the growing concerns towards global environmental qualities and sustainable feedstocks supplies. In this regard, biomass appeared to be one of the potential feedstocks because it is generally carbon neutral and essentially renewable. Utilizations of biomass and its substitutions to the non-renewable feedstocks have been subject of interests in recent years. Looking to these prospects, biomass could be used to produce numerous products that ranged from energy, chemicals and materials. However, competing uses of biomass and the possibilities to consume more than one biomass sources have created decision dilemmas with economic uncertainties. Therefore, this thesis has presented the developments and executions of optimization models of biomass supply chain that are considered very important in every screening and planning stages.

Optimization model of biomass supply chain from Chapter 3 has provided industrial solution to Omtec Inc. for their business planning and expansion. With the obtained optimal results, the company could prioritize its future products lines. They are now have informed decision to be more flexible in terms of resources utilizations and products generations. As for this thesis, the developed model in Chapter 3 served a basis for constructing and extending the optimization model to different case studies. The general modelling framework is applicable with minor modifications.

In Chapter 4, the model has considered different case study with the addition of environmental performance from transportation and production activities. Each processing route in the supply chain's superstructure and every transportation network between processing facility has been evaluated in terms of carbon dioxide equivalent emission. This addition has certainly represented two pillars of sustainability which are the economic and the environmental emphases. Furthermore, the developed model is relevant to the country like Malaysia where the studied biomass source is abundant and cheap, and the related policies and incentives are already in place. With the model, the single owner of the supply chain might facilitate other enterprises for future strategic investments related to EFB utilizations.

The results in Chapter 5 has extended the supply chain model with optimal selections of processing routes and transportation modes. In order to achieve this purpose, the previous superstructure was modified to incorporate the products' states so that the transportation modes whether truck, train, barge and pipeline could be assigned. Simultaneously, the selections have also provided both economic and emission values so the supply chain's owner could re-evaluate his initial judgements based on the model that was developed in Chapter 4. This extended model has also eliminated uneconomic processing routes and processing technologies. This will ensure further refinements about the model's parameters could be done in a more strategic way.

6.2 Recommendations for Future Works

Although this research has addressed the modeling and optimization of biomass supply chain for energy, chemicals and materials productions in a comprehensive manner, still some related work requires further investigations, and these include:

- Refine the obtainment of models' parameters with industrial and demonstration data, if this is possible. Otherwise, the parameters could be obtained from individual process simulation results which certainly require lot of efforts.
- Incorporate consideration about technological risk for each of the processing route in the supply chain model. This has been suggested by Omtec Inc. in the final meeting.
- Include a case where the facilities in the supply chain are owned by multiple owners. Each of the owner has different priorities and interests in designing and operating all the facilities.
- Extend the developed model by also considering stochastic behaviors of the economics and financial planning that are related to the biomass supply chain

APPENDIX A (GAMS LOG FILE FOR CHAPTER 3)

```
--- Starting compilation
--- Model 1.gms(303) 3 Mb
--- Starting execution: elapsed 0:00:00.000
--- Generating LP model omtec
--- Model 1.gms(283) 4 Mb
---   274 rows  366 columns  712 non-zeroes
--- Model 1.gms(283) 4 Mb
--- Executing CPLEX: elapsed 0:00:00.047
ILOG CPLEX    Dec 24, 2007 WEX.CP.CP 22.6 035.037.041.wei For Cplex 11.0
Cplex 11.0.0, GAMS Link 34
Cplex licensed for 10 uses of lp, qp, mip and barrier, with 4 parallel threads.
Reading data...
Starting Cplex...
Tried aggregator 1 time.
LP Presolve eliminated 229 rows and 312 columns.
Aggregator did 30 substitutions.
Reduced LP has 15 rows, 24 columns, and 44 nonzeros.
Presolve time =    0.00 sec.
Iteration log . . .
Iteration:     1   Scaled dual infeas =          2325.509998
Iteration:    21   Dual objective     =      22618673.062777
Optimal solution found.
Objective:    22618673.062777
```

```
--- Restarting execution

--- Model 1.gms(283) 2 Mb

--- Reading solution for model omtec

--- Model 1.gms(283) 2 Mb

--- Executing after solve: elapsed 0:00:00.154

--- Model 1.gms(286) 3 Mb

*** Status: Normal completion

--- Job Model 1.gms Stop 05/11/16 23:11:50 elapsed 0:00:00.154
```

APPENDIX B (GAMS LOG FILE FOR CHAPTER 4)

```
--- Starting compilation
--- Model 2e.gms(566) 3 Mb
--- Starting execution: elapsed 0:00:00.015
--- Generating LP model palmoilefb1
--- Model 2e.gms(542) 5 Mb
---   5,401 rows  6,844 columns  12,711 non-zeroes
--- Model 2e.gms(542) 5 Mb
--- Executing CPLEX: elapsed 0:00:00.087
ILOG CPLEX    Dec 24, 2007 WEX.CP.CP 22.6 035.037.041.wei For Cplex 11.0
Cplex 11.0.0, GAMS Link 34
Cplex licensed for 10 uses of lp, qp, mip and barrier, with 4 parallel threads.
Reading data...
Starting Cplex...
Tried aggregator 1 time.
LP Presolve eliminated 5288 rows and 6690 columns.
Aggregator did 74 substitutions.
Reduced LP has 39 rows, 80 columns, and 135 nonzeros.
Presolve time =    0.00 sec.
Initializing dual steep norms . . .
Iteration log . . .
Iteration:     1   Dual infeasibility =          4088.320150
Iteration:    17   Dual objective     = 6035567885334.971700
```

```
Optimal solution found.

Objective:   713642268.623451

--- Restarting execution

--- Model 2e.gms(542) 2 Mb

--- Reading solution for model palmoilefb1

--- Model 2e.gms(542) 3 Mb

--- Executing after solve: elapsed 0:00:00.286

--- Model 2e.gms(544) 3 Mb

*** Status: Normal completion

--- Job Model 2e.gms Stop 05/11/16 23:14:03 elapsed 0:00:00.288
```

APPENDIX C (GAMS LOG FILE FOR CHAPTER 5)

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--- Starting compilation
--- Model 3e.gms(654) 3 Mb
--- Starting execution: elapsed 0:00:00.009
--- Model 3e.gms(602) 4 Mb
--- Generating MINLP model palmoilefb2
--- Model 3e.gms(605) 8 Mb
---   6,540 rows  10,900 columns  20,561 non-zeroes
---   10,153 nl-code  1,770 nl-non-zeroes
---   2,610 discrete-columns
--- Model 3e.gms(605) 6 Mb
--- Executing BARON: elapsed 0:00:00.132
GAMS/BARON    Dec 24, 2007 WIN.BA.NA 22.6 011.000.000.vis P3PC
XPRESS-MP license initialization failed
==============================================================================
                         Welcome to BARON v. 8.1.1
                 Global Optimization by BRANCH-AND-REDUCE
             BARON is a product of The Optimization Firm, LLC.
              Parts of the BARON software were created at the
                University of Illinois at Urbana-Champaign.
              Version Built: WIN Sat Oct 13 20:46:07 EDT 2007
==============================================================================
                     Factorable Non-Linear Programming
==============================================================================
```

```
LP Solver:  ILOG CPLEX
NLP Solver: MINOS
Doing local search
Solving bounding LP
Starting preprocessing LPs
6673 preprocessing LPs remain with estimated completion time 11 secs
Done with preprocessing LPs
Starting multi-start local search
Done with local search
===========================================================================
We have space for 95 nodes in the tree (in 32 MB memory)
===========================================================================
 Iteration    Open Nodes       Total Time      Lower Bound          Upper Bound
      1           1            000:00:57       0.000000D+00          0.483681D+10
      1           1            000:00:57       0.000000D+00         0.483681D+10
      1           1             000:01:17      0.000000D+00         0.170403D+10
     13+          7            000:01:47       0.000000D+00         0.170403D+10
     31+         16            000:02:17       0.000000D+00         0.170403D+10
     78+         40            000:02:48       0.000000D+00          0.170403D+10
*     90          0            000:02:56       0.156111D+10         0.170403D+10
     90           0            000:02:56       0.156111D+10         0.170403D+10
Cleaning up solution and calculating dual
Found feasible solution with value 0.156110661282D+10
```

```
                          *** Normal Completion ***

  LP subsolver time    :            000:02:05,    in seconds:       124.55

  NLP subsolver time   :            000:00:29,    in seconds:        28.97

  All other time       :            000:00:24,    in seconds:        23.80

  Total time elapsed   :            000:02:57,    in seconds:       177.31

       on parsing      :            000:00:04,    in seconds:         4.42

       on preprocessing:             000:00:52,    in seconds:        52.23

       on navigating   :            000:00:01,    in seconds:         1.30

       on relaxed      :            000:00:03,    in seconds:         3.38

       on local        :             000:00:10,    in seconds:         9.92

       on tightening   :            000:00:03,    in seconds:         2.86

       on marginals    :            000:00:00,    in seconds:         0.03

       on probing      :             000:01:43,    in seconds:       103.17

   Total no. of BaR iterations:      90

   Best solution found at node:      90

   Max. no. of nodes in memory:      46


 All done with problem

=================================================================================

Solution      = 1561106612.82 found at node 90

Best possible = 1704028484.94

Absolute gap = 142921872.12 optca = 1E-9

Relative gap = 0.08387 optcr = 0.1
```

```
--- Restarting execution

--- Model 3e.gms(605) 3 Mb

--- Reading solution for model palmoilefb2

--- Model 3e.gms(605) 3 Mb

--- Executing after solve: elapsed 0:02:58.694

--- Model 3e.gms(608) 4 Mb

*** Status: Normal completion

--- Job Model 3e.gms Stop 05/11/16 23:58:46 elapsed 0:02:58.698
```

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