Novel Approach for Integrated Biomass Supply Chain Synthesis and Optimisation

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ABSTRACT

Despite looming energy crises, fossil resources are still widely used for energy and chemical production. Growing awareness of the environmental impact from fossil fuels has made sustainability one of the main focuses in research and development. Towards that end, biomass is identified as a promising renewable source of carbon that can potentially replace fossil resources in energy and chemical productions. Although many researches on converting biomass to value-added product have been done, biomass is still considered underutilised in the industry. This is mainly due to challenges in the logistic and processing network of biomass. An integrated biomass supply chain synthesis and optimisation are therefore important.

Thus, the ultimate goal of this thesis is to develop a novel approach for an integrated biomass supply chain. Firstly, a multiple biomass corridor (MBC) concept is presented to integrate various biomass and processing technologies into existing biomass supply chain system in urban and developed regions. Based on this approach, a framework is developed for the synthesis of a more diversified and economical biomass supply chain system. The work is then extended to consider the centralisation and decentralisation of supply chain structure. In this manner, P-graph-aided decomposition approach (PADA) is proposed, whereby it divides the complex supply chain problem into two smaller sub-problems – the processing network is solved via mixed-integer linear programming (MILP) model, whereas the binaries-intensive logistic network configuration is determined through P-graph framework.

As existing works often focus on supply chain synthesis in urban regions with well-developed infrastructure, resources integrated network (RIN) – a novel approach for the synthesis of integrated biomass supply chain in rural and remote regions is introduced to enhance rural economies. This approach incorporates multiple resources (i.e. bioresources, food commodities, rural communities' daily needs) into the value chain and utilises inland water system as the mode of transport, making the system more economically feasible. It extends the MBC approach for technology selection and adopts vehicle routing problem (VRP) for inland water supply and delivery network.

To evaluate the performance of the proposed integrated biomass supply chain system, a FANP-based (fuzzy analytical network process) sustainability assessment tool is established. A framework is proposed to derive sustainability index (SI) from pairwise comparison done by supply chain stakeholders to assess the sustainability of a system. Fuzzy limits are introduced to reduce uncertainties in human judgment while conducting the pairwise comparison.

To design a sustainable integrated biomass supply chain, a FANP-aided, a novel multiple objectives optimisation framework is proposed. This approach transforms multiple objective functions into single objective function by prioritising each of the objective through the FANP framework. The multiple objectives are then normalised via max-min aggregation to ensure the trade-off between objectives is performed on the same scale. At the end of this thesis, viable future works of the whole programme is presented for consideration.

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LIST OF ABBREVIATIONS

ABB	Accelerated Branch-and-bound Algorithm
AHP	Analytical Hierarchical Process
ANP	Analytical Network Process
BP	British Petroleum
CPO	Crude Palm Oil
DLF	Dried Long Fibre
DOA	Department of Agriculture
EAI	Enterprise Application Integration
EFB	Empty Fruit Bunches
EPA	Environmental Protection Agency
EPU	Economic Planning Unit
ERP	Enterprise Resource Planning
FANP	Fuzzy analytical network process
FFB	Fresh Fruit Bunches
HPS	High Pressure Steam
IAM	Innovation Agency Malaysia
IEA	International Energy Agency
IFAD	International Fund for Agricultural Development
ISI	Inherent Safety Index
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Lice Cycle Impact Assessment
LCO	Life Cycle Optimisation

LP	Linear Programming
MBC	Multiple Biomass Corridor
MCDA	Multi-criteria Decision Analysis
MF	Mesocarp Fibre
MILP	Mix Integer Linear Programming
MINLP	Min Integer Non-linear Programming
MOO	Multi-objective Optimisation
MOT	Ministry of Transport
MPIB	Malaysian Pineapple Industry Board
MPS	Medium Pressure Steam
MSG	Maximal Structure Generator
NLP	Non-linear Programming
PADA	P-graph aided decomposition approach
PEST	Political, environmental social and technological
PIIS	Prototype Inherent Safety Index
PKS	Palm Kernel Shell
POME	Palm Oil Mill Effluent
POST	Parliamentary Office for Science and Technology
RIN	Resources integrated network
RNF	Rural Non-farm
RRMCC	Regional Resource Management Composite Curve
SCORE	Sarawak Corridor of Renewable Energy
S-ERP	Sustainable Enterprise Resource Planning
SI	Sustainability Index
SOO	Single Objective Optimisation

SSCM	Sustainable Supply Chain Management
SSG	Solution Structure Generator
TFN	Triangular Fuzzy Numbers
UN	United Nation
VRP	Vehicle Routing Problem
WSM	Weighted Sum Model

LIST OF SYMBOLS

Sets

a	Index for biomass source
b	Index for processing hub
c	Index for demand
e	Index for utility
g	Index for bioresource g
h	Index for bioresource processing technology h
i	Index for biomass type
j	Index for primary processing technology
k	Index for intermediate product
l	Index for secondary processing technology
m	Index for final product
n	Index for environmental impact
o	Index for social Impact
p, q, r	Index for rural village
s, t	Index for criteria
u	Index for decision maker
y	Index for sustainability indicator

Variables

AC^{GP}	Annualised gross profit
AC^{GP}_{PH}	Annualised gross profit of processing hub
AC^{IN}	Annualised investment cost

AC^{PR}	Annualised production cost
AC^{RE}	Annualised revenue
AC^{TR}	Annualised transportation cost
$\beta_{a,b}$	Binary variable that denotes the selection of route from *a* to *b*
β_b	Binary variable that denotes the selection of hub *b*
$\beta_{b,c}$	Binary variable that denotes the selection of route from *b* to *c*
β_l	Binary variable that denotes the selection of process *l*
C^{IN}	Cost of supply chain
C^{RE}	Revenue of supply chain
D_{total}	Total distance travelled
$F_{a,b}$	Flowrate of biomass *i* from *a* to *b*
$F_{b,in}$	Flowrate of biomass in hub *b*
$F_{b,c}$	Flowrate of product from hub *b* to demand *c*
$F_{b,out}$	Flowrate of product in hub *b*
$F_{e,CON}^{b}$	Utility consumption in hub *b*
$F_{e,EX}^{b}$	Utility exported in hub *b*
$F_{e,GEN}^{b}$	Utility generation in hub *b*
$F_{e,IM}^{b}$	Utility imported in hub *b*
F_g	Flowrate of bioresource *g*
$F_{g,h}$	Flowrate of bioresource *g* to technology *h*
F_i^b	Flowrate of biomass type *i* in hub *b*
$F_{i,j}^b$	Flowrate of biomass type *i* to technology *j* in hub *b*
F_k^b	Intermediate *k* in hub *b*

$F_{k,l}^{b}$	Flowrate of intermediate type *k* to technology *l* in hub *b*
F_{m}^{b}	Flowrate of product *m* in hub *b*
λ	Degree of satisfaction
N_{truck}	Number of trucks
S_{CF}	Carbon footprint of supply chain
S_{CF}^{Fuel}	Carbon footprint of fuel consumption
S_{CF}^{Power}	Carbon footprint of power consumption
$S_{CF}^{Process}$	Carbon footprint of processes
S_{DR}	Death risk of supply chain
S_{GP}	Gross profit of supply chain
S_{ISI}	ISI of supply chain
S_{JO}	Job opportunities created by supply chain
$S_{JO}^{Process}$	Job opportunities created by processing network
$S_{JO}^{Transport}$	Job opportunities created by logistic network
S_{LF}	Land footprint of supply chain
$S_{LF}^{Capacity}$	Proportional land footprint of setting up a hub
S_{LF}^{Hub}	Fixed land footprint of setting up a hub with 1 tonne capacity
S_{WF}	Water footprint of supply chain
S_{WF}^{Fuel}	Water footprint of fuel consumption
S_{WF}^{Power}	Water footprint of power consumption
$S_{WF}^{Process}$	Water footprint of processes
S_{y}	Score for sustainability indicator *y*
S_{y}^{Nor}	Normalised score for sustainability indicator *y*

SI	Sustainability Index
U_p	Cumulative load at village *p*
U_r	Cumulative load at village *r*
w_y	Priority weightage of sustainability indicator *y*
$x_{p,q}$	Binary variable that denotes the flow from village *p* to village *q*
$x_{p,r}$	Binary variable that denotes the flow from village *p* to village *r*
$x_{r,q}$	Binary variable that denotes the flow from village *r* to village *q*
$x_{r,r}$	Binary variable that denotes the flow within village *r*
z_{st}	Comparison ratio of *s* to *t*
z_{ts}	Comparison ratio of *t* to *s*

Parameters

$\mathrm{AC}_{\mathrm{boat}}^{\mathrm{CC}}$	Annualised capital cost of boat
$\mathrm{AC}_{\mathrm{OU}}^{\mathrm{IN}}$	Annualised investment cost of operating unit
$\mathrm{AC}_{\mathrm{OU}}^{\mathrm{TR}}$	Annualised transportation cost of operating unit
BC_e	Buying cost of utility *e*
BC_i	Buying cost of biomass *i*
$\mathrm{C}^{\mathrm{Con}}$	Construction cost of each hub
$\mathrm{C}^{\mathrm{Land}}$	Land cost of each hub
CA_a	Capacity of hub *a*
CA_b	Capacity of hub *b*
CA_c	Capacity of demand *c*
$\mathrm{CA}_{g,\mathrm{depot}}$	Capacity of bioresource *g* at depot
CA_p	Availability of resource at village p

CA_r	Availability of resource at village r
$\mathrm{CA}_{\mathrm{boat}}$	Capacity of boat
$\mathrm{CA}_{\mathrm{truck}}$	Capacity of truck
CC_l	Capital cost of technology *l*
CC_j	Capital cost of technology *j*
$\mathrm{CE}_{e,j}$	Utility consumption of technology *j*
$\mathrm{CE}_{e,l}$	Utility consumption of technology *l*
CFR	Capital recovery factor
$\mathrm{CR}_{h,i}$	Conversion of technology *h* converting bioresource *g* to biomass *i*
$\mathrm{CR}_{\mathrm{j,e}}$	Conversion of technology *j* converting biomass *i* to utility *e*
$\mathrm{CR}_{j,k}$	Conversion of technology *j* converting biomass *i* to intermediate *k*
$\mathrm{CR}_{l,e}$	Conversion of technology *l* converting intermediate *k* to utility *e*
$\mathrm{CR}_{l,m}$	Conversion of technology l converting intermediate *k* to product *m*
D	Distance travelled
$\mathrm{D}_{a,b}$	Distance from *a* to *b*
$\mathrm{D}_{b,c}$	Distance from *b* to *c*
$\mathrm{D}_{p,q}$	Distance from village *p* to village q
EF_m	Emission factor of product *m*
$\mathrm{EF}_{\mathrm{fuel}}$	Emission factor of fuel
$\mathrm{EF}_{\mathrm{power}}$	Emission factor of power
$\mathrm{EF}_{\mathrm{pp}}$	Emission factor of power plant
$\mathrm{F}^{\mathrm{material}}$	Flowrate of material
$\mathrm{FC}_{\mathrm{boat}}$	Fuel consumption of boat
FC	Fuel consumption cost

$\mathrm{Hub}^{\mathrm{N}}$	Number of hubs
HC	Handling cost
l_{st}	Lower bound of pairwise comparison between criteria *s* and *t*
$\mathrm{LR}_{\mathrm{hub}}$	Fixed land requirement for a hub
$\mathrm{LR}_{\mathrm{capcity}}$	Proportional land requirement for a hub with 1 tonne capacity
LS	Lifespan of processing hub
m_{st}	Mode of pairwise comparison between criteria *s* and *t*
$\mathrm{N}_{\mathrm{boat}}$	Number of boats
$\mathrm{N}_{\mathrm{trip}}$	Number of trips
OC_{j}	Operating cost of technology *j*
OC_{l}	Operating cost of technology *l*
PC	Cost of production
$\mathrm{PG}_{\mathrm{pp}}$	Power generation of power plant
RI	Interest rate
$\mathrm{S}_{\mathrm{DR}}^{a,b}$	Death risk for route from *a* to *b*
$\mathrm{S}_{\mathrm{DR}}^{b,c}$	Death risk for route from *b* to *c*
$\mathrm{S}_{\mathrm{ISI}}^{l}$	ISI of process *l*
$\mathrm{S}_{\mathrm{ISI\_CC}}^{l}$	ISI of chemical corrosiveness
$\mathrm{S}_{\mathrm{ISI\_chemical}}^{l}$	ISI of chemical properties of process *l*
$\mathrm{S}_{\mathrm{ISI\_CI}}^{l}$	ISI of chemical interaction
$\mathrm{S}_{\mathrm{ISI\_ES}}^{l}$	ISI of equipment
$\mathrm{S}_{\mathrm{ISI\_EX}}^{l}$	ISI of explosiveness
$\mathrm{S}_{\mathrm{ISI\_FL}}^{l}$	ISI of flammability

$S^{l}_{ISI\_HRM}$	ISI of heat of main reaction
$S^{l}_{ISI\_HRS}$	ISI of heat of side reaction
$S^{l}_{ISI\_IN}$	ISI of process inventory
$S^{l}_{ISI\_PP}$	ISI of process pressure
$S^{l}_{ISI\_process}$	ISI of design specification of process *l*
$S^{l}_{ISI\_PS}$	ISI of process structure
$S^{l}_{ISI\_PT}$	ISI of process temperature
$S^{l}_{ISI\_TE}$	ISI of toxic exposure
S^{m}_{JO}	Job opportunities created for every tonne of *m* produced
S^{Truck}_{JO}	Job opportunities created for each truck owned
S^{L}_{y}	Lower limit of sustainability indicator *y*
S^{U}_{y}	Upper limit of sustainability indicator *y*
SC_{m}	Selling cost of product *m*
SC_{e}	Selling cost of utility *e*
u_{st}	Upper bound of pairwise comparison of criteria *s* to *t*
v_{u}	Influence weight of stakeholder *u*
WR_{fuel}	Water requirement of fuel consumption
WR_{m}	Water requirement of production of *m*
WR_{power}	Water requirement of fuel consumption
WR_{pp}	Water consumption of power plant
$\hat{Z}$	Comparison matrix
$\hat{z}_{st}$	Fuzzy judgment between criteria *s* and *t*

CHAPTER 1

INTRODUCTION

1.1 Background

Fossil fuels have been providing us with a very useful energy source. They are the main pillars that support the chemical industries as major raw materials for the synthesis and productions of numerous chemical intermediates and products. To date, it is still dominant in energy markets, accounting about 85.5% of global energy usage (BP, 2019b). Approximately 90% of organic chemicals are derived from fossil fuels (Maity, 2015) for chemical industries.

The global fossil fuels consumption for energy and chemical production has increased 2.5 times since 1971 (IEA, 2019). Growing population and improving living standards are key drivers behind the growing global energy and chemicals consumption. World population is projected to increase by around 1.7 billion people to reach nearly 9.2 billion people by 2040 (BP, 2019a), causing the depletion of non-renewable fossil fuels at an alarming rate. On the other hand, fossil fuel burning results in the release of greenhouse gasses into the earth's atmosphere especially carbon dioxide (CO_2) which, since the Industrial Revolution, has risen approximately 46% in atmospheric concentration due to large scale utilisation of fossil fuels (EPA, 2020). This contributes to the global warming phenomena we witness throughout the globe over the past decades up till now.

The utilisation of limited fossil fuels along with its undesirable environmental impacts is unsustainable and detrimental in fulfilling human needs. Growing awareness of global sustainability requires a radical transformation of fossil fuels into sustainable and renewable feedstock to achieve future energy security and fuel diversification (Klemeš and Lam, 2009). While there is a broad portfolio of renewable resources (e.g. wind, hydro, solar, geothermal and nuclear energies) available to address multiple sustainability challenges, biomass remains an important and competitive option that appears to be a promising renewable feedstock for energy generation and chemical synthesis. Biomass is influencing current energy development significantly and its contribution to world energy consumption is predicted to increase from 4% to around 15% by 2040 (BP, 2019a). Hence, new concepts have continuously been evolved, seeking possibilities in using biomass to produce an array of fuels and multitudes of chemical products. The following section reviews biomass resources as renewable feedstocks, along with the development and challenges faced in converting biomass to bioproducts.

1.2 Biomass Resources as Renewable Feedstocks

A comprehensive definition of biomass, including all the potential renewable bioresources, is *"any organic matter that is available on a renewable or recurring basis, including dedicated energy crops and trees, agricultural residues, algae and aquatic plants, wood and wood residues, animal wastes, and other waste materials usable for the production of energy, fuels, chemicals and materials* (Kamm et al., 2006). Biomass originates from plants which naturally capture carbon dioxide from atmosphere during photosynthesis. In contrasts, fossil resources originate from carbon dioxide stored by nature through the photosynthesis of ancient organisms million years ago. Large scale utilisation of fossil resources for energy and chemical productions thus releases ancient carbon and other greenhouse gases into earth's atmosphere (Ghatak, 2011). Therefore, utilisation of biomass as feedstock for these activities is a greener and cleaner option. Besides, this waste-to-wealth strategy provides an opportunity to solve waste management issue.

In past decades, food crops have been extensively utilised for first generation biofuels productions. However, "fuel vs food" ethical problems appear to be the most controversial issue in the production of first-generation biofuels (Sharma et al., 2013). Commercialisation of first-generation biofuels led to an expansion in the number of crops being diverted away from the global food market. This trend has shifted to second-generation and third-generation biofuels which utilise non-food crops such as lignocellulosic biomass, organic residues and algae as feedstock for biofuels generation.

Following tactics in crude oil and petrochemical industries, biomass-based manufacturing aims to substitute crude oil-based manufacturing of carbon containing products such as biochemicals, materials and polymers (Sadhukhan et al., 2014). They now target to produce chemical building blocks, simple yet highly functionalised molecules for industrial applications via organic synthesis. Compared to crude oil, biomass-based production is capable to synthesise more chemicals varieties due to the presence of oxygen, a wider range of functional groups and bond types in raw biomass. Therefore, biomass has potential to make significant contributions to the future of sustainability, given its functional ability to directly substitute fossil fuels in many applications with corresponding reduction in carbon emissions, while also improving environmental and socio-economic services (Smeets et al., 2007).

Despite having similar complex composition as petroleum, the structure of biomass is not as homogeneous as compare to petroleum-based feedstock. This is because biomass is derived naturally through photosynthesis process. Due to different environments, species and many other factors, the quality of biomass may vary (Kamm et al., 2006). Note also, that unlike petroleum-based feedstocks which usually has a low extend of form functionality, biomass typically take the form of large polymer chains (Schmidt and Dauenhauer, 2007). As a result, research on biomass-to-bioproducts is extensive from a technical perspective.

Over the last decade, there has been plenty of research on conversion technologies for biomass-to-bioproducts. However, a transition from non-renewable resources to renewable feedstocks is more than a technology shift in terms of type of conversion technology; it is a transition in supply chains as well. Fossil fuel is sourced in single points and has good storage and transportation properties, whereas biomass, which remains biologically active, has poor transportation and storage properties. Besides, it is often scattered in multiple locations. Thus, it is inherently challenging to handle and transport biomass because it induces a variety of economic, environmental and societal implications. This also explains why biorefineries require higher investment and operational costs which inhibit market penetration and fair competition with traditional oil refinery industries. Instead of technical reasons, economic conditions and supply chain co-ordination are the main barriers that hinder increased biomass utilisation (McCormick and Kåberger, 2007). It is hence justified to address and assist in this transition from a supply chain perspective. Section 1.3 provides an overview of biomass supply chain and its current development.

1.3 Overview of Biomass Supply Chain

The structure of the global market for biomass and the associated supply chains is evolving dynamically. Extensive literature is available on supply chain design and management of good produced by traditional industries that are well-developed and have a long history, such as automobile and consumer goods. But these models could not be applied directly in the biomass industry because biomass supply chains deal with uncertainty in availability and quality, whereas supply chains for traditional good deal with demand uncertainty to determine the economic viability of the industry. Traditionally, biomass has been used for either small scale energy production (mostly thermal) or animal feed. However, an emerging practice for biomass utilisation is to generate and synthesise energy and biochemical in a large-scale integrated biorefinery. The increasing complexity of this system spurs the need for developing sophisticated customised supply chain planning and coordination methodologies, as opposed to the well-explored traditional supply chain management.

As shown in recent reviews (Iakovou et al., 2010, Gold and Seuring, 2011; Sharma et al., 2013), there has been a significant amount of research on biomass supply chains over the last couple of years. Generally, a biomass supply chain or network can be referred as *an operational management method that integrate and optimise discrete processes that consist of biomass supply, processing facilities, customer and logistics in order to lessen the environmental impact and the cost of production along the life cycle of the bioproducts*. It helps to determine the location and conversion technology of processing facilities as well as the logistic network of supply and demand. A proper biomass supply chain planning ensures biomass resources to be delivered at the conversion facility at the correct time, in the correct quantity and in the desired shape, size and quality.

Since past decades, there has been various approaches applied in biomass supply chain synthesis and optimisation models such as *mathematical optimisation approaches, metaheuristic approaches, IT-driven approaches and hybrid approaches*. These biomass supply chain models generally have an objective of minimising costs associated with production, logistics, and operation of biorefineries along with providing an efficient chain structure (De-Mol et al., 1997). Their focuses are often biomass utilisation in urban region with established infrastructures and technologies. These models help to give insight into potential future production of biofuel and biochemicals from biomass and help in decision-making at all levels of planning (Akgul et al., 2010). Whilst the concept of biomass supply chain is promising, there are several challenges that have hindered its development. Section 1.4 discusses further on these challenges.

1.4 Problem Statement

Biomass is no doubt highly beneficial to modern societies as an alternative sustainable feedstock for energy generation and chemicals synthesis. Yet the development of global biomass industry is still at preliminary levels. It has been estimated that only 10% of the worldwide potential biomass resources are utilised (Alakangas et al., 2012) due to barriers in the developing of biomass supply chain, identified below:

i. Biomass diversity and unutilised biomass – biomass with substantial economic potential is not utilised and models are unable to involve multiple types of biomass;
ii. Centralisation and decentralisation of processing/pre-processing facilities – it is often very complex to decide whether to centralise or decentralise processing/pre-processing facilities along the supply chain to ensure optimum performance of the supply chain;
iii. Remote and rural regions – scattered biomass supply and limited transport infrastructure have always been the key challenge in the development of biomass industry in remote and rural regions;

iv. Sustainability assessment and analysis – There is a lack of a systematic assessment tool to assist stakeholders in decision-making along the development of the entire biomass value chain; and

v. Multiple contradictory attributes in optimisation and synthesis – Most previous work focuses on a single attribute or co-current duo attributes in the optimisation and synthesis of biomass supply chain. However, it always involves multiple attributes and they often contradict each other.

1.5 Research Aim

As discussed in the previous section, the lack of systematic approach to synthesise, assess and optimise biomass supply chain in both urban and rural regions has been the stepping stone in the commercialisation of bioproducts. Thus, this research aims to contribute to the body of knowledge by proposing a *novel approach for integrated biomass supply chain synthesis and optimisation* to address the challenges mentioned in Section 1.4.

1.6 Research Objective

The aim of this research is accomplished by developing systematic approaches with the following objectives:

i. To integrate multiple types of biomass, especially unutilised ones to synthesis an integrated biomass supply chain;

ii. To determine the optimum structure, whether centralised or decentralised, of an integrated biomass supply chain;

iii. To develop a systematic framework for the synthesis of an integrated biomass supply chain in rural and remote regions;

iv. To evaluate the sustainability performance of an integrated biomass supply chain; and

v. To synthesise and optimise an integrated biomass supply chain based on multiple objectives.

1.7 Research Contribution

This research has made several novel contributions in the development of biomass supply chain synthesis and optimisation. The main contributions yielded from this research are stated as follows:

i. The proposed multiple biomass corridor (MBC) concept integrates multiple utilised and unutilised biomass into current biomass supply chains, making the entire system more diverse and effective;

ii. P-graph-aided decomposition approach (PADA) helps to reduce the complexity on deciding the structure of the supply chain (centralised or decentralised), improving the economic performance of the entire system;

iii. Resources integrated network (RIN) incorporates bioresources, food commodities and community's needs into supply chains in rural and remote regions. By integrating inland water transport into the system, the value chain is expected to be beneficial to the rural communities in achieving healthier rural economy;

iv. FANP-based (fuzzy analytical network process) sustainability assessment and analysis framework give detailed qualitative information of biomass supply chain to aid shareholders in decision-making; and

v. FANP-based synthesis and optimisation model allows the synthesis and optimisation of sustainable biomass supply chain based on different contradicting attributes and objectives.

1.8 Thesis Outline

The thesis is organised into 9 chapters. Chapter 1 introduces the background of the study and highlights the challenges faced in the development of biomass supply chain system along with the aim, objectives and contribution of this work. In Chapter 2, a critical review on the biomass potential of Malaysia and state-of-the-art biomass supply chains. This is followed by a review of biomass supply chain synthesis and optimisation approaches developed in the past. At the end of Chapter 2, research gaps are highlighted as the motivation for this research. Based on these gaps, several scopes are proposed in Chapter 3. These scopes are addressed with a systematic methodology, which will be discussed in detail at the end of Chapter 3. A novel multiple biomass corridor concept is introduced in Chapter 4 to integrated multiple types of biomass in supply chain synthesis and optimisation. The economic performance of the model is then improved by considering centralised and decentralised biomass supply chain structures via P-graph approach in Chapter 5. Next, Chapter 6 will focus on the design and synthesis of biomass supply chain in rural and remote regions, while Chapter 7 proposes a systematic framework to assess and analyse the sustainability of biomass supply chain. This is then followed by a development of multiple objectives synthesis and optimisation model for biomass supply chain in Chapter 8. For Chapter 9, concluding remarks are given to provide a complete overview of the novel approach developed. Finally, future research work is enumerated at the end of Chapter 9 to provide further opportunities on improving the completeness of the systematic approaches developed in this thesis.

Chapter 2

Literature Review

2.1 Introduction

Chapter 2 aims to provide a literature review on the existing work on biomass supply chain system from concept to modelling. This chapter starts by investigating and studying the current biomass utilisation background in Malaysia in Section 2.2. Next, Section 2.3 explores the current biomass processing technologies available. The data collected from these two sections will be used as input to the case studies of this thesis. In Section 2.4, the transition of conventional supply chain to biomass supply chain is discussed and a comprehensive definition is given to integrated biomass supply chain as a foundation for this entire work. Each of the stages along the supply chain is analysed with its challenges highlighted. The chapter is then narrowed down to the in-depth review of synthesis and optimisation approaches in addressing these supply chain problems in Section 2.5. Finally, based on the given review, the research gaps are conclusively identified and discussed in Section 2.6.

2.2 Biomass Utilisation Background in Malaysia

In Malaysia, the biorefinery industry is one of the key developments of the Eleventh Malaysia Plan (EPU, 2015). Innovation Agency Malaysia predicts that the biorefinery industry could provide 410 MW of electricity, reduce carbon emission by 12 % and generate a gross national income of 30 billion MYR (IAM, 2018). Since agricultural sector is the backbone of Malaysia’s economy, it is bestowed with significant amount of biomass resources. Annually, a minimum of 168 million tonnes of biomass waste is generated within the country (IAM, 2018). The agricultural and forestry sectors produce many residues that have no other commercial values and which existence has created disposal problems to the country. In addition, the Department of Environment has discouraged burning these materials due to pollution and possible forest burning problems. Therefore, the best solution to this problem is to utilise these wastes as renewable feedstocks for energy generation and chemical synthesis in developing the biorefinery industry.

With more than 5.74 million hectares of palm oil plantation (Nambiappan et al., 2018), Malaysia is one of the world's largest in palm oil production with total world palm oil production at about 28% and world exports at about 33% (MPOC, 2019). It is estimated that 234 Mt of palm biomasses are produced annually, based on 239 Mt of fresh fruit bunches (FFB) processed (Shafie et al., 2012). These biomasses include empty fruit bunches (EFB), palm kernel shell (PKS), mesocarp fibre (MF) and palm oil mill effluent (POME). Part of these biomasses are currently being used as organic fertiliser for mulching (Yoon et al., 2011), fuel for boiler (Sumathi et al., 2009) or taken as by-products and further processed into value-added products, such as dried fibres, briquette and pellet, biogas, and energy pack.

The massive amount of palm oil biomass potentially results in less utilisation in other available bioresources presently available in Malaysia. Therefore, a wider option in terms of bioresources, plantation development plan and resources application should be introduced to solve security issues. Paddy is one of the rich bioresources in Malaysia as rice is a crucial part of every Malaysian diet. According to Department of Agriculture Malaysia, paddy planted area throughout Malaysia is estimated to be 700 thousand hectares while the average paddy yield is around 2.5 metric tonnes per hectare (KRI, 2019). The cultivation of rice produces paddy straw and rice husk as wastes. Due to their high energy content (15.09 MJ/kg for paddy straw and 15.84 MJ/kg for rice husk), they appear to be an attractive alternative substitute for energy synthesis (Lim et al., 2012). Rice husk (Kartini, 2011) and paddy straw (Munshi, et al., 2013) can also be used to produce silica ashes as renewable pozzolanic additive in cement paste but it is still not commonly utilised in commercial building systems on large scales. Instead of using this paddy biomass as building materials, it is more common to be used in mineral mix for composting (Theeba, et al., 2012).

Another agricultural waste that is abundantly available in Malaysia is sugarcane bagasse, but its utilisation is still limited. Improper treatment of sugarcane bagasse causes land, water and air contamination by means of leaching, dusting and volatilisation (Mannan and Ganapathy, 2004). In general, 1 tonne of sugarcane generates 300 kg of bagasse in the production of sugar (Bezerra et al., 2016). This lignocellulose residue has a strong potential in the generation of energy (Ramjeawon, 2008). It can also be converted into furfural as a renewable substitute for synthetic resins (Uppal, et al., 2008). Other applications of sugarcane bagasse are as feedstock to produce second-generation ethanol (Cardona, et al., 2010) and paper paste (Pattra, et al., 2008).

Dating back to the last decade, the pineapple industry is the oldest agricultural-based export-oriented industry in Malaysia. Although its scale relatively smaller as compared to palm oil industry, it contributes greatly in the country's socio-economic development. Annually, there are about 21 thousand metric tons of canned pineapples produced in our country (MPIB, 2018). During processing, a substantial amount of waste comprising solid and liquid waste is produced. Waste disposal is problematic as the biomass is prone to microbial spoilage due to the high moisture and sugar content. As common practice, the solid waste is utilised as fertiliser or animal feed (Lim and Matu, 2015). While the liquid waste contains high levels of carbohydrates, it can be used as a source of carbon for microbial fermentation to produce methane (Rani and Nand, 2004), ethanol (Choonut, et al., 2014), citric acid (Chau and David, 1995) and formic acid.

As one of the top producers of sago starch in the world, sago biomass is one of the potential biomass types to be considered in Malaysia (Singhal et al., 2008). Sago palm is mostly grown in the state of Sarawak and it possesses about 55 thousand hectares of sago plantation area (DOA Sarawak, 2016). During sago starch production, sago fibre and sago bark are produced as waste. Due to limited transport infrastructure in Sarawak, sago bark is usually combusted directly for firing or disposed around the mill as flooring material. Sago fibre on the other hand is utilised as animal feed or disposed along with wastewater (Awg-Adeni et al., 2010). However, both lignocellulosic wastes contain residue starch which can be converted into glucose as sustainable precursor that can be further refined to higher value biofuel and biochemical (Awg-Adeni et al., 2013).

In conclusion, utilisation of massive biomass is one of the potential key development of the economics of Malaysia. It does not only contribute to the national economy but also a greener way to solve disposal problems in the country (Lam, et al., 2010). Although the economic potential of multiple types of biomass are explored intensively in many researches, they are yet to be integrated into the current biomass supply chain system. To harness the value of these wastes in supply and demand networks, their respective processing technologies are discussed in detailed in the following section.

2.3 Biomass Processing Technologies

There are various conversion technologies that can transform biomass resources into biofuel and biochemical. This section therefore reviews the up-to-date treatment of all the available technologies for biomass conversion. It is noted that most of the biomass processing technologies can be generally categorised into pre-processing, biochemical, physical and thermochemical processing technologies. In a biorefinery, biomass feedstocks are firstly pre-processed into various precursors via pre-processing technologies. These precursors are then converted into various value-added products via biochemical, physical or thermochemical conversion technologies. The categorisation is summarised as shown in *Figure 2-1*.

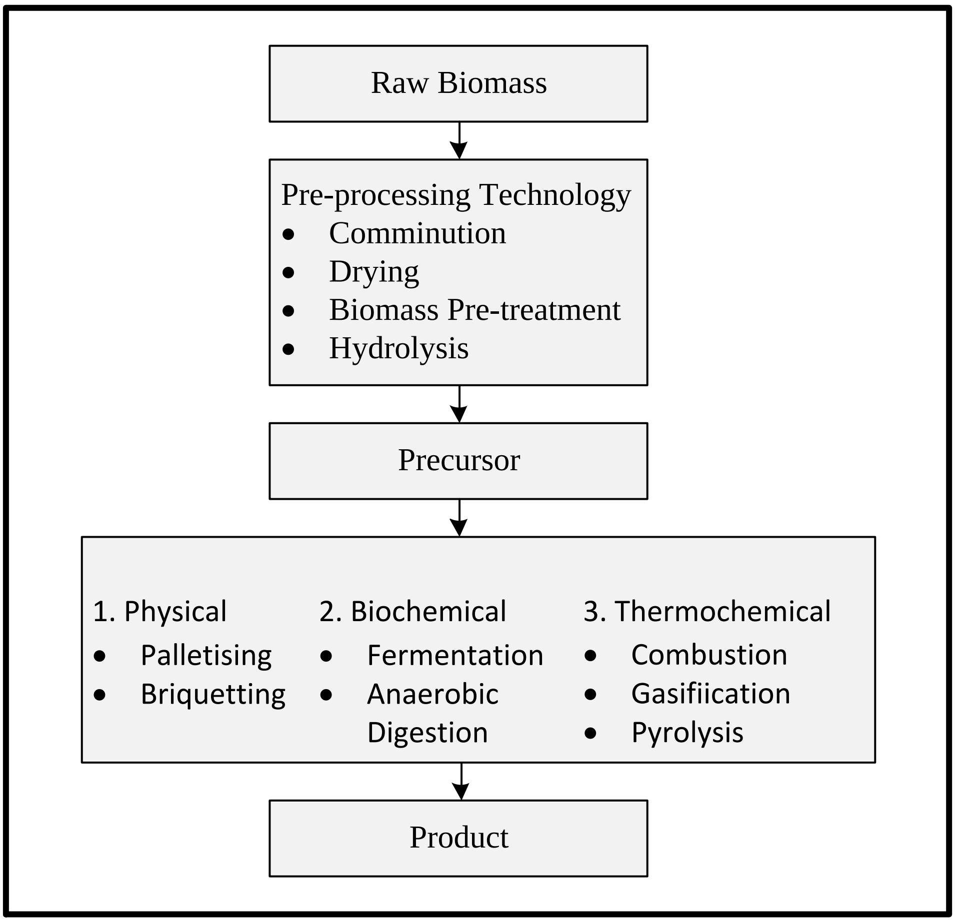

Figure 2-1: Biomass processing technologies classification

2.3.1 Biomass Pre-processing

The biomass pre-processing technologies can be generally grouped into comminution, drying, biomass pre-treatment and hydrolysis. Comminution is a mechanical treatment process that reduce the size of a feedstock to enhance the digestibility of lignocellulosic biomass (Palmowski and Muller, 1999) with the application of energy. Coarse size reduction, chipping, shredding, grinding and milling are amongst the different mechanical size reduction methods that have been commonly used in the industry. These methods increase the available specific surface area and reduce both the degree of polymerisation and cellulose crystallinity (Sun and Cheng, 2002). The optimal performance of a comminution machine can be nominally expressed in term of size reduction ratio (i.e. initial size/ final size). Different size reduction ratios imply different power consumptions for different comminution machine. Note that the optimal performance of a comminution machine is nominally affected by the initial size and moisture content of the feedstock. Note also that a small amount of moisture is normally removed during comminution.

Drying is a mass transfer process that remove the moisture from biomass feedstocks via heat. There are various dryers used in the industry, including rotary dryer, flash dryer and belt dryer. The use of different drying mediums (e.g. hot air, flue gas, etc) and the number of stages (e.g. single pass, three passes, etc) imply different energy consumption of the dryer. The performance of a dryer can normally be expressed in term of moisture removal ratio (i.e. discharge moisture/ feed moisture). Note that the optimal performance of a dryer is nominally affected by the moisture content and the size of the inlet feedstock.

Biomass pre-treatment is an important pre-processing system in biorefinery application where the main objective is to alter the macroscopic and microscopic structure of lignocellulosic biomass to increase digestibility. It is normally accomplished by utilising different additives (such as chemicals) and/or energy to form a solid/component that can be used to generate more soluble oligosaccharides (e.g. glucan, xylan) and monosaccharides (e.g. glucose, xylose, etc) than the native biomass feedstock. There are various pre-treatment technologies which can potentially be used in industry, such as dilute acid pre-treatment, alkaline pre-treatment, steam pre-treatment, ammonia fibre explosion pre-treatment, etc.

Hydrolysis is a subsequent processing step which normally comes after pre-treatment. The main objective is to convert the holocellulose (i.e. cellulose and hemicellulose) of lignocellulosic biomass into fermentable sugars (e.g. glucose, xylose, etc) with addition of water. Chemical and enzymatic hydrolysis methods have been proved to be potentially successful in industrial application. However, enzymatic hydrolysis is commonly employed which uses different enzymes (e.g. cellulases, xylanases, etc) to effectively enhance the hydrolysis process.

2.3.2 Physical Conversion

Physical conversion processes are processes which do not chemically change the composition of biomass, but only perform physical alterations. Pelletising and briquetting are common physical conversion to compress the biomass into solid biofuel with the shape of pellet and briquette. Since solid biofuel is very sensitive to moisture, the biomass then needs to be dried to obtain the pulverising condition in cases where the moisture content of biomass is high. After the drying process, biomass is pulverised in accordance with the required size of solid biofuel. Pulverised biomass is then prepared by using screw extrusion system, by which the biomass is extruded continuously by a screw through a taper die to produce pellet or briquette.

2.3.3 Biochemical Conversion

Biochemical conversion is a biological pathway that involves the use of bacteria, microorganisms and enzymes to degrade biomass and converts it into different value-added products at lower temperature and low reaction rate (Cherubini and Strømman, 2010). Biochemical conversion technologies consist of anaerobic digestion and fermentation.

Fermentation is a metabolic process that converts fermentable sugars into recoverable products such as alcohols and organic acids. Prior to fermentation, high sugar content biomass is firstly hydrolysed into fermentable reducing sugars, catalysed by cellulose enzymes. The sugars formed are then fermented into desired products by respective bacteria and yeast. It has also been proven that pre-treatment before hydrolysis can improve the overall efficiency of fermentation (Sun and Cheng, 2002).

Anaerobic digestion is a series of biological processes which microorganisms break down and convert biodegradable material into methane and carbon dioxide in the absence of oxygen over a temperature range from about 30°C to 65°C. It consists of hydrolysis, acidogenesis, acetogenesis and methanogenesis (Speece, 1983). Like fermentation, the complex and insoluble organic compounds in the biomass are first hydrolysed into simple soluble compounds in the presence of enzymes excreted by fermentative bacteria. These soluble compounds are then converted into long chain fatty acids and then acetate in acidogenesis and acetogenesis phases respectively. In the final stage, methane-producing bacteria will convert the acetic acid into methane gas. This conversion technology is commonly used for recycling and treating of wet organic waste and wastewater in chemical industries.

2.3.4 Thermochemical Conversion

Unlike biochemical conversion and physical conversion, thermochemical conversion usually occurs at higher temperatures. The most common and traditional thermochemical conversion technology is direct combustion — the burning of biomass in the presence of oxygen. Furnaces and boilers are used typically to produce steam for use in district heating/cooling systems or to drive turbines to produce electricity. In a furnace, biomass burns in a combustion chamber, converting the biomass into heat which is then distributed in the form of hot air or water. In a boiler, the heat of combustion is converted into steam. Steam can be used to produce electricity, mechanical energy, or heating and cooling. A boiler's steam contains 60-85% of the energy in biomass fuel.

Gasification is one type of thermochemical conversion process. It is typically operated in temperature ranging from 600°C to 1400°C with a controlled supply of oxidant (e.g. oxygen, air or steam) to chemically break down the biomass into syngas (Cherubini, 2010). Syngas is a type of gas mixture consisting of mainly hydrogen and carbon dioxide and with little amount of steam, methane and carbon monoxide. It can be used as subsequent feedstocks to produce liquid fuels via Fisher-Tropsch process. Additionally, syngas can also be used for heat and power generation via combustion.

On the other hand, pyrolysis is another thermochemical conversion process in which biomass is converted into biooil and biochar in the absence of oxidant (Bridgwater, 2003).

There are two types of pyrolysis — fast pyrolysis and slow pyrolysis. Slow pyrolysis operates in lower temperature, low heating rate and longer residence time to maximise the production of biochar; while fast pyrolysis operates in higher temperature, higher heating rate and short residence time to maximise the production of biooil (Bridgwater and Peacocke, 2000). Note that biomass must be dried and size-reduced before it can be fed to the thermochemical conversion processes, regardless if it is a pyrolysis or gasification process.

Despite intensive researches on biomass conversion technologies, the feasibility of biomass as an alternative renewable feedstock is still controversial as the transition from fossil fuel to biomass is more than just conversion technology shift. Instead, it should be addressed from a supply chain perspective. Hence, Section 2.4 will introduce the concept of biomass-to-bioproducts supply chain and discuss the elements within it in depth.

2.4 The Concept of Integrated Biomass-to-Bioproducts Supply Chain

"Supply chain management", is a term that was first coined by Oliver and Webber (1982) when they discovered the advantages of the integration of core business entities of procuring, production, sales and distribution into a single unified structure. The advent of supply chain support for manufacturing in fact happened long before the term came into context in the mid 80's. In general, a typical supply chain network contains four business functions — supplier, manufacturer, distribution centres, and customers (Beamon, 1998). It involves the movement of products and information from the inward-bound to the outward-bound of the business as well as from the supply source to the demand end-user (Stevens, 1989). Supply chain management aims to integrate all the business functions in such a way that the products are always synthesised and distributed at the right place, at the right time; fulfilling desired quantity, quality, and service level along with minimising the total cost of the system (Simchi-Levi et al., 2013). The capability of the supply chain is influenced by the level of coordination and integration between the parties and entities, along with effective and efficient movement of materials and data (Beamon, 1998).

The supply chain management in biomass industry on the other hand is a big management conundrum. It plays an important role in the management of bioenergy and biochemical production processes (Gold and Seuring, 2011). Biomass supply chain differs from traditional supply chains due to several variabilities. These sources of variability include the uncertainty in biomass availability and supply due to weather and seasons, the fluctuating chemical and physical properties of biomass (Cundiff et al., 1997), the geographical distribution and low transport density of feedstock, the local transportation system and the distribution of infrastructure, as well as the inconsistent demand (Fiedler et al., 2007). The complexity deepens owing to the large number of stages which encompass the entire biomass value chain. A consistent, continuing, cheap and uninterrupted of desired quality raw feedstock is essential for the biorefinery industry to be competitive. To ensure long-term viability of a biorefinery project, a proper assessment of the transport, storage and handling of biomass is required (Sukumara et al., 2015). Biomass supply chain management therefore manages the uncertainty in biomass source and availability, whereas the traditional supply chain management copes with market uncertainty to identify the economic feasibility of the industry.

To date, there are several definitions for biomass-to-bioenergy supply chain management. In general, it is identified as the integration of 5 discrete processes of harvesting and collection, pre-treatment, storage, transport and energy conversion (Iakovou et al., 2010). In biomass-to-bioproducts supply chain, the downstream segment, delivery of biofuels and biochemical to the customer and the interaction with market demand appear to be important activities. In this paper, the product demand therefore is embedded as the last activity in the chain and these activities are categorised into 4 components. Hence, biomass supply chain is defined *as an integrated value chain with 4 components: production and management of biomass, integrated biorefinery, distribution of product, as well as logistics linked through the flow of materials and information* as shown in *Figure 2-2*. There are no distinct boundaries amongst these 4 components in the chain as they are interdependent and interconnected, resulting in varying degrees of overlapping. Materials change forms and characteristics as they move through the chain and a huge number of logistical networks are possible depending on the crops supply and product demand.

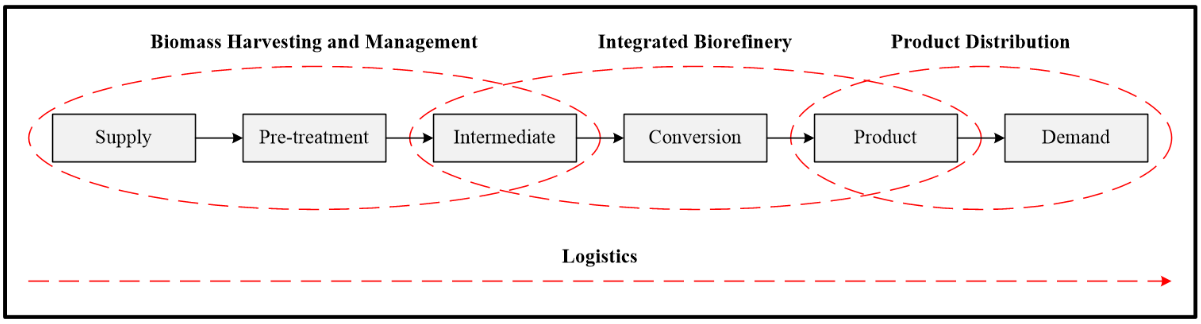

Figure 2-2: Integrated biomass supply chain

2.4.1 Biomass Harvesting and Management

The biomass source of supply is the initial point for the planning and development of the entire supply chain. In the context of biomass as renewable feedstock for biofuel production, it is most often defined as any organic or biological material which is obtainable on a renewable or regular basis and referred as lignocellulosic (Sadhukhan et al., 2014). It is usually plants or plant-based materials which are not meant for feeding purpose such as rice husk, paddy straw, palm kernel shell, empty fruit brunches and etc. Industrial and municipal waste which is biodegradable is also considered as part of biomass. In biomass harvesting and management, the main scope to deal with are availability of raw biomass, composition of raw material, allocation of feedstock, harvesting scheduling and decentralisation of pre-treatment activities.

One of the major barriers in this component is to maintain constant and continuous supply of biomass feedstock. Biomass is locally available but the seasonality of biomass results in uncertain availability. Considering the climate change and weather, these uncertainties could result in an inconsistent and even shortage of biomass supply. The current feedstock management systems are not able to meet the requirements of a large scale biorefinery development, because they are initially designed for small or medium scale of handling and logistics requirements (Hoogwijk et al., 2003). In such circumstances, supply chain efficiency and careful inventory planning would become vital for the survival of large-scale biorefinery.

One of the characteristics of biomass is the simple fact that it remains a biologically living matter and it is also chemically active throughout the supply chain. The biological activity will alter the composition (i.e. carbon, moisture and ash content) of the material. This will affect the product conversion in the biorefinery. From a supply chain efficiency perspective, it is critical to evaluate and maintain the quality of the biomass from time to time. Proper harvesting schedule can ensure the quantity and quality of the raw biomass is within specification limit when it is sent to the doorstep of respective biorefineries. Decentralisation of pre-treatment activity from the biorefinery to the biomass collection site can maintain the desired specification of the raw material before transportation to the processing facility. For instance, oil palm frond juice is extracted from the raw oil palm frond at the palm plantation as the juice has a longer storage life as compared to the raw frond. Pre-treatment such as pelletising converts dense biomass into less dense biomass to reduce handling, storage and transportation cost. This explains why pre-treatment can be categorised as an activity in this component in certain cases especially biomass with short shelf life and low transport density.

2.4.2 Integrated Biorefinery

In a processing facility or biorefinery, raw biomass is first pre-processed into more useful processable segments, known as platforms or precursors (Fernando et al., 2006). These fractions are then converted into biofuel and biochemical (Sadhukhan et al., 2014). *Figure 2-3* illustrate the concept of an integrated biorefinery. An integrated biorefinery that allows multiple feedstocks, swapping between feedstocks and blending of biomass source of a distinct or similar nature into a highly diverse portfolio product is a critical element in the entire supply chain. Like traditional chemical plant, this complex system is capable to perform material and energy exchange to fulfil their needs and attain self-sufficiency. However, the primary focus here revolves around the conversion of pre-treatment and major processing technologies. The detailed design of the biorefinery is not the main concern.

One of the challenges that will be faced in this stage will be the determination of facility location. This decision is usually made by considering sources of biomass, transportation infrastructure and logistics cost. Conversion technology selection decisions also play a key role in structuring of biomass supply chains as it influences/constraints the choice of biomass materials, type of pre-processes needed, capital and operational costs of the supply chain. Given biomass feedstock and product requirement, a series of cost-effective technologies can be selected and thus form the optimum technology network for biorefinery. Prior to that, the sizing of the hub can also be estimated. In addition, the configuration of biomass supply chains is very much dependent on the choice between centralized (with a large biorefinery) and decentralized (with several distributed small biorefineries) production hub (Yılmaz and Selim, 2013). Usually, decentralised processing facility is preferred for biomass with low transport density and vice versa for cost saving purpose.

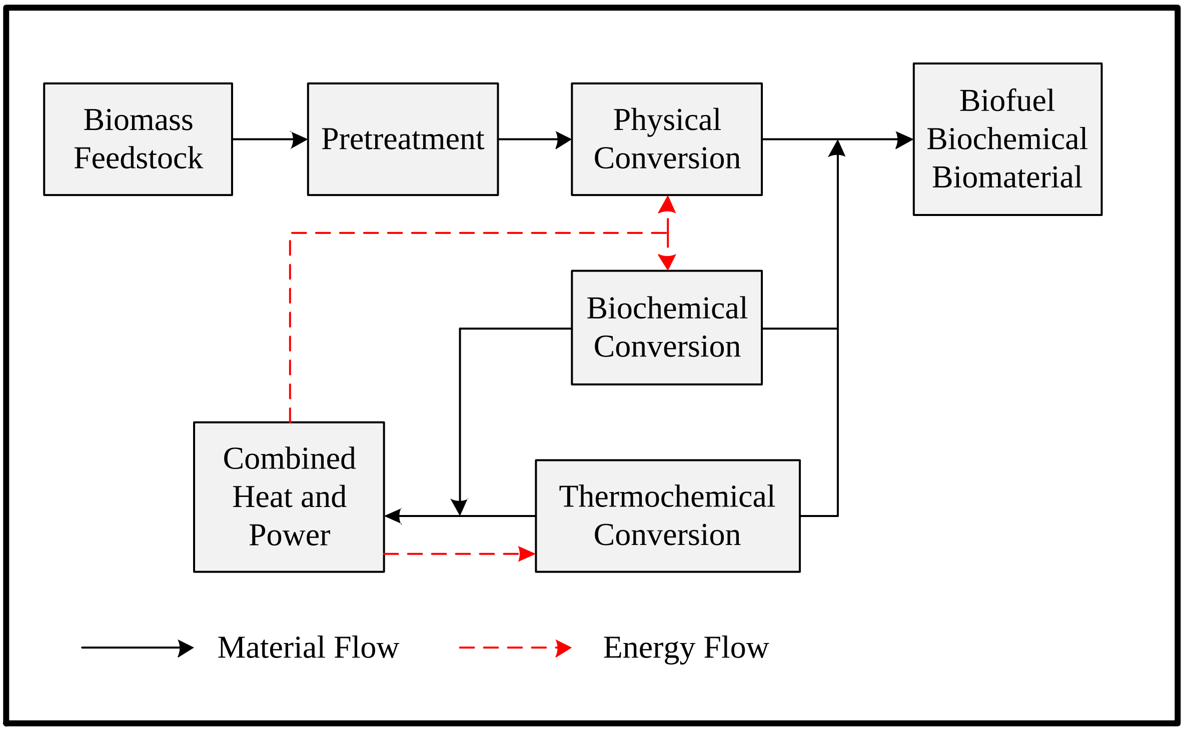

Figure 2-3: Integrated biorefinery concept (Kasivisvanathan et al., 2014)

2.4.3 Product Distribution

Product distribution is defined as the way the products move from the manufacturer to the consumer. In a biomass-to-bioproducts supply chain, final products are distributed to the customers according to their respective demands. The logistic network will be greatly affected by products types. Products in biomass supply chain as mentioned can be grouped into two: bioenergy including as heat, electricity and biofuels; and biochemicals that can be utilised for various industry applications to satisfy human necessity such as nutrition, food and beverages, pharmaceuticals, fertilisers, biodegradable plastics, surfactant, fibres, adhesives, enzymes and more. Bioenergy as a renewable source of energy has the potential to compete with fossil fuels due to the significance of such industry in future needs of sustainable energy. Biochemicals on the other hand gain more attention in the industry especially high value products for pharmaceutical and cosmetics industry. Bioenergy in the form of electricity and heat can be transferred to the end user via electricity grid and convection. Solid, liquid or gaseous biofuels and biochemicals on the other hand can be transported through the existing transportation system (land, water or air). The supply chain must be robust and flexible in order to cope with the fluctuating market demand.

2.4.4 Logistics

The link that integrates all the components in the supply chain is logistics. Transportation and storage connect all the activities together. Typical decisions related to transport phase in biomass supply chain are transportation mode, schedule as well as transport routes and network. Transportation mode refers to the type and capacity of transportation whether by land, sea or air. It depends on infrastructure systems around the source, processing and demand point. Given the capacity of the transport and the amount of feedstock or product, the number of the transports can be determined. To ensure the feedstock and product can reach the doorstep of respective biorefinery and customer on time, the schedule plays an important part. In fact, the decision of the complete transportation network and route is made to minimise supply chain costs and travel time, and to minimize the environmental impacts of supply chain activities.

From an inventory planning perspective, choosing a proper storage system for certain biomass and bioproducts is a complex decision to make. It involves a large degree of uncertainty about the quality and quantity of biomass and bioproducts (Kudakasseril Kurian et al., 2013). Choosing an appropriate location for biomass storage facilities is not only influenced by the type and characteristics of biomass materials but is also constrained by transportation options (Allen et al., 1998). For bioproducts, it is affected by the amount and type of material. Further, some researches recommended on-field biomass storage and on-site products storage to reduce the overall delivery costs (Huisman et al., 1997). In summary, *Figure 2-4* presents the challenges and scopes to be addressed along the supply chain. To address these problems, supply chain synthesis and approaches are discussed in the next section.

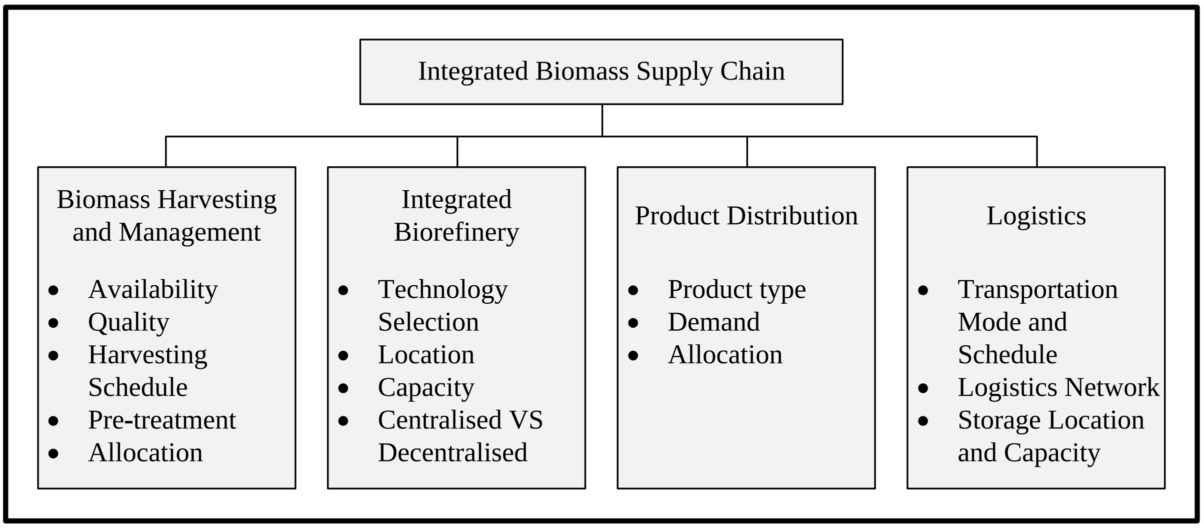

Figure 2-4: Challenges and scopes along the supply chain

2.5 Biomass Supply Chain Synthesis and Optimisation Model

Biomass supply chain synthesis and optimisation models developed via different approaches aim to help in making decisions and solving problems at all levels of the value chain. These approaches can be categorised as: (i) mathematical optimisation approach, (ii) metaheuristic approach, (iii) hybrid approach and (iv) IT-driven approach.

2.5.1 Mathematical Optimisation Approach

Mathematical programming involves the development of mathematical models that represent real-world situations and can be used to determine the optimal outcome. In general, a mathematical programming model involves an objective function, decision variables and constraints. This implies that the values of the decision variables are determined in a way that the objective function is optimised while the values satisfy the restrictions put forward in the constraints. Based on formulations in different cases or scenarios, these mathematical optimisation models can range from relatively straight-forward linear programming (LP) to the increasingly complex mixed-integer linear programming (MILP), non-linear programming (NLP) and mixed-integer non- linear programming (MINLP) which depict real life scenario more accurately (Grossmann, 2002). The main benefit of using traditional mathematic programming is that the optimum solution can always be found. However, it is not capable to solve the real-time optimisation of large-scale problem which are often fuzzy (Turan et al., 2012). The required computation time will increase significantly when the problem sizes increases.

In the early days, mathematical programming often focused on single objective optimisation (i.e. economic) (Robinson and Satterfield, 1998). It is utilised to solve resource allocation and product distribution (Lee and Kim, 2000). The focus is often on the logistics and transportation network (Syam, 2002). Recently, Lam et al. (2013) emphasised technology selection as one of the important components in biomass supply chain. A two-stage mathematical optimisation model was proposed for optimal technologies selection as well as logistics and transportation network. Uncertainties inherent in biomass value chain can also be capture via mathematical modelling (Peidro et al., 2009). Sustainable biomass supply chain management does not focus on the economic aspect entirely. Mathematical model is capable to cope with multiple objective optimisation, taking into consideration other aspects (i.e. environment and social) (Liang, 2008). Scheduling is one of the scopes which can be solved using mathematical models. Amaro and Barbosa-Póvoa (2005) proposed mathematical formulation to optimise scheduling for industrial supply chain. The list of works which implemented mathematical modelling technique in solving sustainable supply chain problem are tabulated in *Table 2-1*.

Table 2-1: Mathematical optimisation approach in biomass supply chain synthesis

Year	**Author**	**Remark**
1998	Robinson and Satterfield	Development of a multidisciplinary framework that considers the interactions among firm's distribution strategy, market share and cost
1998	Petrovic et al.	Introduction of a supply chain fuzzy model to analyse the behaviour of a serial supply chain under uncertainty
1999	Dogan and Goetschalckx	Formulation of a mixed integer programming and an integrated design methodology based on primal decomposition for multi-period production and distribution system in supply chain
1999	Li and O'Brien	Introduction of an integrated decision model for assessing potential partners in a supply chain
2000	Lee and Kim	Introduction of a hybrid simulation approach which is a specific problem-solving procedure to solve the production distribution problem
2001	Jayaraman and Pirkul	Development of a heuristic procedure to plan and coordinate production and distribution facilities for multiple commodities supply chain
2002	Syam	Extension of the traditional location models by introducing several logistic components

Table 2-1 (cont'): Mathematical optimisation approach in biomass supply chain synthesis

Year	Author	Remark
2002	Cakravastia et al.	Development of an analytical model of the supplier selection process in designing a supply chain network
2003	Jayaraman and Ross	Solving of the new combinatorial problem that incorporates cross-docking in supply chain environment by using simulated annealing methodology
2003	Yan et al.	Introduction of a strategic production-distribution model that considers bills of materials for supply chain design
2004	Amaro and Barbosa-Póvoa	Introduction of a discrete model to ease the decision-making process at the operation level of supply chain
2004	Erol and Ferrell Jr	Development of an integrated methodology to solve two fundamental decisions making, i.e. assigning suppliers to warehouse and warehouse to customer
2004	Chen and Lee	Formation of a multi-product, multi-stage and multi-period scheduling model to deal with multi-echelon supply chain network with multiple goals
2005	Amaro and Barbosa-Póvoa	Synthesis of a new continuous-time mathematical formulation for the optimal schedule of supply chains
2005	Ryu	Presentation of a multi-level programming framework in capturing complex supply chain decision making
2005	Graves and Willems	Formulation of a two-state dynamic model to minimise the total supply chain cost which includes cost of goods sold, safety stock cost and pipeline stock cost
2005a	Guillén et al.	Development of a two-stage stochastic model to consider of the effect of uncertainty in production
2006	Amiri	Presentation of a computational study in investigating coordinating production and distribution planning
2006	Liang	Development of an interactive fuzzy multi-objective linear programming to solve transportation problems

Table 2-1 (cont'): Mathematical optimisation approach in biomass supply chain synthesis

Year	Author	Remark
2008	Guo and Tang	Introduction of an evaluation model to analyse the feasibility of planning by comparing the planned cost with the anticipated cost
2008	Liang	Development of a fuzzy multi-objective linear programming model with piecewise linear membership function to solve the integrated multi-product and multi-period production/ distribution planning problem
2009	Peidro et al.	Formulation of a fuzzy mathematical programming model to consider uncertainty for supply chain planning
2010	Franca et al.	Introduction of a multi-objective stochastic model to evaluate the financial risk in supply chain via Six Sigma
2010	Xu and Zhai	Utilisation of fuzzy number to depict customer demand and investigate the optimisation of the vertically integrated two-stage supply chain of different scenarios
2012	Paksoy et al.	Development of a fuzzy multi-objective programming model to minimize the total transportation cost
2012	Seifert et al.	Development of a model for three-echelon supply chain with price-only contracts
2012	Afshar and Haghani	Formulation of a mathematical model that controls the flow of commodities from sources through the supply chain and finally to the recipients
2012	Li and Womer	Development of a mathematical model to optimise the sourcing and planning decision simultaneously while exploiting their trade-offs
2013	Ramezani et al.	Introduction of an evaluating technique to evaluate the systematic supply chain configuration maximizing the profit, customer responsiveness and quality as objectives of the logistic network
2013	Lam et al.	Development of a two-stage optimisation model for the optimal operation and logistics management of the waste

Table 2-1 (cont'): Mathematical optimisation approach in biomass supply chain synthesis

Year	Author	Remark
2013	Ng et al.	Synthesis of an optimal rubber seed supply network which maximise the utilisation of rubber seed oil by using mixed integer linear programming
2014	Ng and Lam	Development of a functional clustering approach integrated in an industrial resources' optimisation
2014	Čuček et al.	Formulation of a MILP model for multi-period synthesis for regional biorefinery supply network
2015	Ng et al.	Introduction of a novel algebraic method for supply chain development which allows concurrent set-up of material allocation
2015	Paulo et al.	Development of a MILP model to determine the optimal design of the residual forestry biomass to power generation in Portugal
2016	De Meyer et al.	Optimisation of strategic and tactical decisions in biomass supply chain via a MILP programming model
2017	Syu and Lee	A two-stage optimisation approach which applies linear programming for regional energy planning with biomass utilisation
2019	Foo	Formulation of a simple linear programme model for the optimum allocation of palm biomass among its sources and demands
2019	Ling et al.	Development of an integrated mathematical optimisation approach for the synthesis of a bioelectricity supply chain

2.5.2 Metaheuristic Approach

While mathematical programming models seek for the optimal value of the decision variables, heuristic approaches will look for satisfactory, but not necessarily optimal solutions to solve complex problems in reduced runtimes. Publications applying heuristics to optimise upstream biomass supply management distinguishes three different heuristics algorithms, i.e. genetic algorithm, ant colony optimisation and bee algorithm. These heuristics are known as population-based heuristics which use a population of solutions which evolve during a given number of iterations, also returning a subset of the population of solutions when the stop condition is fulfilled.

To overcome the coordination problem in supply chain network synthesis, Akanle and Zhang (2008) proposed a heuristic algorithm, called genetic algorithm, to dynamically solve the supply chain synthesis problem. During past decades, genetic algorithm has often been implemented to solve single-objective and multi-objective optimisation problems in production and operational management that are non-deterministic, polynomial-time hard (NP-hard). Recently, genetic algorithm technique has been modified to suit each specific problem. The publications related to genetic algorithm implemented in supply chain management are listed in *Table 2-2*.

Table 2-2: Genetic algorithm in biomass supply chain synthesis

Year	Author	Remark
2002	Syarif et al.	Development of a spanning tree-based genetic algorithm to solve the logistic system design in supply chain
2005	Gen and Syarif	Proposal of a spanning tree-based genetic algorithm to solve the production and distribution problem in supply chain with the aim of minimizing the cost
2005	Truong and Azadivar	Proposal of a methodology which integrated mixed integer programming and genetic algorithm to determine optimal supply chain configuration

Table 2-2 (cont'): Genetic algorithm in biomass supply chain synthesis

Year	Author	Remark
2008	Lin et al.	Development of an agent-based distributed coordination mechanism that integrates negotiation techniques with genetic algorithm for scheduling
2009	Yun et al.	Solve a multistage supply chain problem via a genetic algorithm approach with adaptive local search scheme
2009	Altiparmak et al.	Proposal of a solution procedure based on steady-state genetic algorithm with a new encoding structure for the synthesis of a single-source, multi-product and multi-stage supply chain network
2010	Zegordi et al.	Solve of a a two-stage supply chain optimisation via gendered genetic algorithm which considered two different chromosomes with non-equivalent structure
2010	Chang	Proposal of a genetic algorithm which combines the co-evolutionary mode and constraint-satisfaction mode capacity in order to shorten the solving time
2010	Kannan et al.	Solve multi-echelon, multi-period, multi-product closed loop supply chain model by using genetic algorithm
2010	Che and Chiang	Solve a multi-objective optimisation of a build-to-order supply chain via Pareto genetic algorithm
2011	Yeh and Chuang	Development of an optimum mathematical planning model for green partner selection via genetic algorithm
2012	Zamarripa et al.	Proposal of genetic algorithm to solve the supply chain planning under uncertainty
2014	Ghasimi et al.	Development of a novel model for defective goods supply chain network via genetic algorithm
2014	Bandyopadhyay and Bhattacharya	Modification of the non-dominated sorting genetic algorithm to solve a tri-objective supply chain problem
2015	Pasandideh et al.	Utilisation of non-dominated sorting genetic algorithm and non-dominated ranking genetic algorithm to solve a multi-product, multi-period three echelon supply chain

Table 2-2 (cont'): Genetic algorithm in biomass supply chain synthesis

Year	Author	Remark
2017	Maharana et al.	Application of genetic algorithm to optimise the production of biofuels by multiple factors
2019	Sadeghi and Haapala	Design of genetic algorithm to optimise renewable energy supply chain logistics costs and carbon footprint

On top of that, another swarm-based optimisation model, or bee algorithm has been introduced by Pham et al. in 2005. Like ant colony optimisation, bee algorithm is also a nature-inspired heuristic. Bee algorithm is an algorithm that mimics foraging behaviour of honeybees to find the best source of food. Recently, bee algorithm has proven to be a more powerful optimisation tool which is able to determine better Pareto solutions for the supply chain network synthesis problem, compared with the aforementioned ant colony optimisation technique (Mastrocinque et al., 2013). A list of works which applied bee algorithm in supply chain management are tabulated in *Table 2-3*.

Table 2-3: Bee algorithm in biomass supply chain synthesis

Year	**Author**	**Remark**
2010	Koc	Improvement bee algorithm via neighbourhood size change and site abandonment strategy
2013	Mastrocinque et al.	Proposed bee algorithm in dealing with multi-objective supply chain model to find the optimum configuration which minimise the total cost and total lead time
2013	Teimoury and Haddad	Implementation of bee algorithm to solve the parallel batch production scheduling in a supply chain
2013	Chen and Ju	Proposal of a novel artificial bee colony algorithm for solving the mixed-integer nonlinear supply chain network model

Table 2-3 (con't): Bee algorithm in biomass supply chain synthesis

Year	Author	Remark
2014	Yuce et al.	Development of an enhanced bee algorithm with adaptive neighbourhood search and site abandonment strategy to solve the multi-objective supply chain model
2014	Zhang et al.	Proposal of the hybrid artificial bee colony algorithm to solve the environmental vehicle routing problem with minimisation of overall travel distance and travel time
2016	Zhang et al.	Introduction of artificial bee colony-based approach for supply chain design
2019	Chen et al.	Artificial bee colony algorithm is used to reveal the performance of combined cooling, power and heat generation.

Another technique which also has been widely used is ant colony optimisation. This technique is another nature-inspired meta-heuristic that mimics the behaviour of ant colonies and the evaporation effect of the pheromones during their food search process. Despite that unguaranteed optimum solutions, it provides a useful compromise between the amount of computation time necessary and the quality of the approximated solution space (Moncayo-Martínez and Zhang, 2011). Ant colony optimisation was initially used to solve the decision-making problems which involve only single objective function (Bullnheimer et al., 1999). Recently, it has been proven that ant colony optimisation is capable to solve many real-world problems efficiently and effectively. In supply chains, it is commonly used to solve capacity planning (i.e. centralisation vs decentralisation), resource allocation and scheduling problem. *Table 2-4* shows the list of works which implemented ant colony optimisation technique in supply chain management.

Table 2-4: Ant Colony optimisation in biomass supply chain synthesis

Year	Author	Remark
2004	Silva et al.	Development of an integrated framework which merged concept of agents and ant colony
2009	Silva et al.	Introduction of ant colony optimisation technique to solve the supply chain management
2009	Wang	Development of a two-phase ant colony algorithm to design a multi-echelon defective supply chain
2009	Wang and Chen	Propose an ant algorithm to address capacity planning and resource allocation of decentralised supply chain
2011	Moncayo-Martínez and Zhang	Proposal of a Pareto ant colony optimisation to solve the multi-objective supply chain design problem
2013	Moncayo-Martínez and Zhang	Proposal of a modified ant colony optimisation which utilised a bi-objective max-min function to solve the supply chain problem
2014	Moncayo-Martínez and Recio	Determination of a set of supply chain configurations by using the Pareto ant colony optimisation
2015	Cheng et al.	Improvement of ant colony optimisation to solve the scheduling problem for the production in supply chain
2015	Wang and Lee	Proposal of a revised ant colony optimisation to improve the original ant algorithm by using efficient greedy heuristic to solve the supply chain problem
2016	Beltramo et al.	Application of ant colony optimisation model to identify the significant process variables of a biogas production process
2019	Yu et al.	Extension of ant colony algorithm and fuzzy model for supply chain joint inventory management and cost optimisation
2020	Chen at al.	Optimisation of operating parameters of combustion in a biomass briquette chain boiler through ant colony algorithm

2.5.3 Hybrid Approach

Hybrid approach employs mathematical modelling together with theoretical and hierarchical approaches such as pinch graphical approach, life cycle analysis and game theory for decision-making in supply chains. One of the very first hybrid models was proposed by Lam et al. (2010). He combined Pinch graphical approach together with mathematical modelling to optimise the regional biomass supply chain carbon footprint minimisation. It is a demand-driven approach that utilises Regional Resource Management Composite Curve (RRMCC) an analogy of the Process Integration approach to show the energy imbalances helping in the trade-off of resources management. This approach provides straightforward information on how to manage the surplus resources in a region.

Life cycle analysis (LCA) is an important concept in the design of sustainable supply chain. It is the most scientifically reliable method (Ness et al., 2007), that was introduced to measure environmental impact of a product, starting from extraction of raw materials, production, distribution, remanufacturing, recycling up to final disposal (Srivastava 2007). Gungor and Gupta (1999) commented that LCA assesses the impact of a product on the environment based on the materials and energy used and wasted through its production, usage and disposal (Finnveden and Moberg, 2005). Government regulations are also an added factor for organisations to work towards LCA. ISO 14040 has also been developed for LCA to provide general framework, terminology and principles. Moreover, these standards provide transparency and consistency in LCA studies (Cambero and Sowlati, 2014). Generally, LCA can be divided into 4 stages: (i) defining the goal and scope of study, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA) and (iv) interpretation. It is worth noting that, LCA results are strongly dependent on the methodological choices and parameters associated with each analysed case. Therefore, it should not be used to provide the basis of comparative declarations of the overall environmental preferability among the products. Nevertheless, LCA results are useful to compare environmental impacts of the alternative configurations of a supply chain. Life cycle optimisation (LCO) can be applied to synthesise an optimum supply chain (Wan et al., 2016). Many studies related to LCA implemented in sustainable supply chain synthesis are summarised in *Table 2-5*.

Table 2-5: LCA in biomass supply chain synthesis

Year	Author	Remark
2008	Laínez et al.	Application of LCA to evaluate the environmental impact while IMPACT 2002 + methodology is selected
2010	Nwe et al.	Integration of LCA indicators and dynamic simulation for supply chain design and action
2011	Guest et al.	Conduction of a LCA for biomass-based combined heat and power plant.
2011	Kostin et al.	Optimisation of environmental performance of bioethanol sugar supply chain with LCA
2012	Pucker et al.	Conduction of a greenhouse gas and energy analysis for a biomass supply chain
2014	Murphy et al.	Application of LCA to evaluate greenhouse gases emission and primary energy balances in Ireland
2015	Ren et al.	Life cycle cost organisation of biofuel supply chain under uncertainties via interval linear programming
2016	Cambero et al.	Economic and life cycle environmental organisation of forest-based biorefinery
2016	Lim and Lam	Introduction of biomass element life cycle analysis for biomass supply chain optimisation
2020	Singlitico et al.	Integration of LCA and techno-economic analysis in a spatially explicit optimisation model for biomass supply chain

Game theory was firstly introduced by Von Neumann and Morgenstern (1947) and has been widely used as a useful approach applied in various research fields. It offers a valuable tool in the identification of dominant strategy for increasing performance along each objective (Zhao et al., 2012). There are many research works have commented and discussed about the application of game theory (normally cooperatives game) to the supply chain as show in *Table 2-6*. In addition, several game models have been formulated for application to sustainable supply chain. For instances, evolutionary game model (Zhu and Dou, 2007), differential game model (Chen and Sheu, 2009), bargaining model (Sheu, 2011), oligopoly game model (Nagurney and Yu, 2012) and dynamic evolutionary game model (Barari et al., 2012). It is worth to note that the major limitation in the previous work is the lack of interaction between the up-stream and down-stream business. Thus, as a natural extension of research works, the future studies should consider the coordination issues in biomass supply chain (Zhao et al., 2010).

Table 2-6: Game theory in biomass supply chain synthesis

Year	Author	Remark
2004	Cachon and Netessine	Introduction of Game theory to solve the supply chain coordination problem
2007	Huang et al.	Optimisation of the supply chain network design using three-move dynamic game-theoretic approach
2007	Zhu and Dou	Development of an evolutionary game model to investigate effect of government subsidies and penalties
2008	Nagarajan and Sošić	Application of cooperative bargaining model to allocate profit between supply chain members
2009	Chen and Sheu	Creation of a differential game model to design an environmental regulation strategy
2009	Esmaeili et al.	Proposal of several game model of seller-buyer relationship in a supply chain

Table 2-6 (cont'): Game theory in biomass supply chain synthesis

Year	Author	Remark
2010	Zhao et al.	Application of cooperative game theory approach to address the supply chain coordination issues
2011	Sheu	Derivation of bargaining game model to seek negotiation in supply chain management
2011	Huang et al.	Utilisation of three-level dynamic non-cooperative game model for multiple decisions in supply chain network
2012	Barari et al.	Introduction of a dynamic evolutionary game model to solve the coordination of players in supply chain
2012	Nagurney and Yu	Utilisation of an oligopoly game model to design a sustainable fashion industrial supply chain
2012	Zhao et al.	Application of game theory to select appropriate strategies in supply chain to maintain sustainability
2013	Zamarripa et al.	Application of game theory optimisation based tool to improve the decision making of supply chain
2015	Tang et al.	Analysis of palm biomass supply chain in Malaysia via game theory approach
2017	Tang et al.	Determination of an optimal non-cooperative strategy by achieving Nash equilibrium through game theory
2019	Gao et al.	Allocation of profit in collaborative bioenergy and biofuel supply chains through game theory

P-graph framework was initially introduced by Friedler et al. (1992). It has been widely implemented in systematic optimal design, including industrial processes synthesis and supply chain network synthesis. This framework has been proven to be highly effective in solving industry-scale process synthesis problems. One of the attractive attributes of this approach is that it can generate optimum and near-optimum solutions simultaneously. P-graph is a directed bi-partite graph associated with several combinatorial instruments. First are the axioms that must be satisfied for combinatorial feasible solution structures and algorithms which ensures the consistency of the resulting maximal structure and solution networks. These algorithms include maximal structure generator (MSG), solution structure generator (SSG) and accelerated branch-and-bound (ABB) algorithm. Generally, MSG defines the structure model; SSG generates each of the solution structure; and ABB determines the optimum structure by using an improved branch-and-bound algorithm. *Figure 2-5* represents a P-graph with operating units O1, O2 and O3 and following materials M1, M2, M3, M4, M5 and M6.

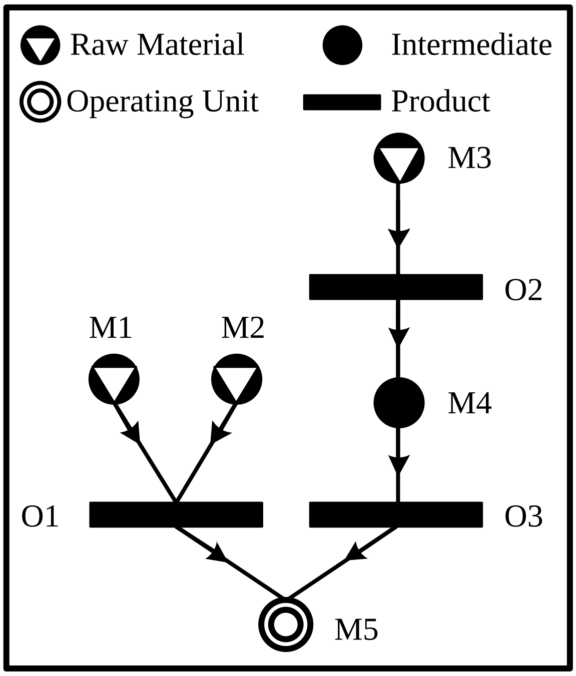

Figure 2-5: P-graph illustration

Recently, the applications of P-graph are extended to several fields, including synthesis of azeotropic distillation system (Feng et al., 2003), reaction pathway identification (Fan et al., 2012), logistics design (Barany et al., 2011), evacuation route planning (García-Ojeda et al. 2013), retrofit planning (Chong et al., 2014), biomass supply chain synthesis and optimisation (Lam et al., 2010). Other publications related to the use of P-graph approach in supply chain synthesis and optimisation are tabulated in *Table 2-7*.

Table 2-7: P-graph in biomass supply chain synthesis

Year	Author	Remark
2009	Fan et al.	Application of P-graph to synthesise an optimal and/or near-optimal enterprise-wide supply network
2010	Lam et al.	Optimisation of regional energy supply chain via P-graph approach
2011	Süle et al.	Extension of the algorithms and software of P-graph for generating optimal and near-optimal supply network with given reliability of each production option
2011	Barany et al.	Proposal of P-graph framework in solving vehicle assignment problem in a supply network
2012	Kalauz et al.	Proposal of extended P-graph methodology, algorithm and software to improve supply networks where quality is measured by cost and response time
2013	Bertok et al.	Introduction a methodology to model the supply chain as well as to synthesise optimal and alternative solutions while considering of structural redundancy
2013	Lam	Extended P-graph approach to address supply chain systems, carbon emission reduction system and cleaner production process synthesis
2013	Vance et al.	Proposal of a computer-aided methodology for designing a sustainable energy supply chain by using P-graph
2017	Aviso et al.	Development of a P-graph-based multi-period optimisation model for sustainable integrated energy system
2018	Benjamin et al.	Extension of P-graph methodology for long-term planning and developing of robust bioenergy parks whole considering uncertainty in supply and demand
2019	Aviso et al.	Development of P-graph methodology for the optimisation of biochar-based carbon management network

2.5.4 IT-driven Approach

IT-driven model reflects the current advances in IT for improving supply chain efficiency. IT-driven models aim to integrate and coordinate various phases of supply chain planning on a real-time basis using application software so that they can enhance visibility throughout the supply chain. Multi-agent technology is one of the common computerised systems which was firstly introduced by Swaminathan et al. (1998). By using this technique, supply chain is structured as a virtual library of structural elements (i.e. production and transportation) and control elements (i.e. flow, inventory, supply and demand). All of them are represented by agents that interact with each other in order to determine the optimal configuration. The major strength of this technique over the conventional mathematical modelling is its flexibility. It can interpret new information from time to time, allows exchange between agents and also enables new policies (Ahn, et al. 2003). Despite all the benefit mentioned above, finding an appropriate methodology to coordinate the agents is still a major challenge. *Table 2-8* shows the list of publications which utilised multi-agent technology in supply chain management.

Table 2-8: Multi-agent technology in biomass supply chain synthesis

Year	Author	Remark
1998	Swaminathan et al.	Development of a simulation-based framework for developing customised supply chain model
2000	Fox et al.	Investigation of the issues and present the solutions for the construction of agent-oriented software architecture
2003	Kaihara	Formulation of the supply chain as a discrete resource allocation problem with dynamic environment
2004	Silva et al.	Development of an integrated framework which merged concept of agents and ant colony

Table 2-8 (cont'): Multi-agent technology in biomass supply chain synthesis

Year	Author	Remark
2005	Fischer and Gehring	Development of a multi-agent system for supporting of transhipments of imported finished vehicles
2005b	Guillén et al.	Application of an agent-oriented simulation system to model each entity in supply chain as an independent agent
2006	Lin and Lin	Introduction of multi-agent negotiation mechanism to solve a distributed constraint satisfaction problem
2006	Liang and Huang	Development of a multi-agent system to simulate a supply chain where agents operate these entities with different inventory system
2006	Zhang et al.	Proposal of an agent-based approach to integrate, optimise, simulate, restructure and control the supply network dynamically and cost effectively
2007	Zhang and Zhang	Formulation of an agent-based consumer decision-making model that considers consumers' psychological personality and interactions in market
2008	Forget et al.	Proposal of a multi-behaviour planning agent model using different planning strategies when decisions are supported by a distributed planning system
2008	Lin et al.	Utilised an agent-based distributed coordination mechanism that integrates negotiation techniques with genetic algorithm to plan for scheduling
2009	Lim et al.	Proposal of an interactive agent bidding mechanism which performs dynamic integration of process planning and production
2009	Hanafizadeh and Sherkat	Proposal of a fuzzy-genetic learner model based on multi-agent system in order to tackle the distribution and allocation problems in supply chain

Table 2-8 (cont'): Multi-agent technology in biomass supply chain synthesis

Year	Author	Remark
2011	Giannakis and Louis	Development of a framework for the design of a multiple agent-based decision support system and risk mitigation in supply chain management
2013	Zolfpour-Arokhlo et al.	Development of a route planning model based on multi-agent system for supply chain management
2014	Sitek et al.	Introduction of the concept of hybrid multi-agent approach for the modelling and optimisation of supply chain management
2014	Pal and Karakostas	Proposal of a multi-agent and web service framework for collaborative material procurement systems
2015	Fu and Fu	Development of a new intelligent system framework of adaptive multi-agent system to improve the cost collaborative management in supply chain
2016	Zhang et al.	Application of a multi-agent framework for the development of a biomass supply chain model for China's biomass generation power plants
2018	Esmaeilzadeh	Development of agent-based model for multi-source biomass purchase, planning and scheduling for a power plant
2019	Jonkman et al.	Synthesis of an eco-efficient biomass supply chain through a multi-actor optimisation model
2020	Rahgu et al.	Optimisation of environmental sustainability of forest biomass logistic using geographical information system and agent-based modelling

One of the commonly used models in supply chain is enterprise resource planning (ERP) — an integrated information system which is designed to automate and integrate all the business processes and operations together. Kandananond (2014) pointed out that the development of sustainable supply chain will not be possible and feasible without the implementation of ERP in organisation. In order to improve the effectiveness and successful rate of the implementation of the ERP in the organisation, a lot of research works have been conducted since last decade as shown *Table 2-9*.

Table 2-9: ERP in biomass supply chain synthesis

Year	Author	Remark
2000	Al-Mashari and Zairi	Reengineering of supply chain by applying ERP
2002	Marinos and Zahir	Introduction of Enterprise Application Integration technique to integrate ERP and supply chain
2003	Lee et al.	Integration of enterprise with ERP and EAI
2005	Kelle and Akbulut	Information sharing, cooperation and cost organisation in supply chain management by implementation of ERP
2006	Koh and Saad	Integration of supply chain management and ERP
2007	Basoglu et al.	Demonstration of organisation adoption of ERP
2010	Law et al.	Introduction of full lifecycle of ERP
2010	Kuhn and Sutton	Introduction of a continuous auditing system in ERP
2011	Goni et al.	Introduction of the critical success factor for ERP
2012	Lopez and Salmeron	Dynamic risk modelling in ERP
2012	Brooks et al.	Introduction of Sustainable Enterprise Resource Planning (S-ERP)
2014	Kandananond	Implementation of ERP in sustainable supply chain system
2015	Leu and Lee	Implementation of ERP in manufacturing using value engineering methodology and Six Sigma tools to improve customer response time and operational efficiency in terms of work-in-process and turnover of materials.
2018	Chofreh et al.	Design of S-ERP framework based on sustainability and decisional paradigms to improve the sustainability processes in organisations

However, some of research works showed that despite implementing ERP systems in organisations, some of them still fail to achieve the supply chain integration due to its complexity, low flexibility and collaboration with others (Themistocleous et al., 2001). To solve this problem, Enterprise Application Integration (EAI) technology is proposed to support the efficient incorporation of information system, resulting in integration of supply chain. On the other hand, the supply chain development has raised environmental pressure and attendant business responsibilities. Moreover, climate change, resource depletion, human health problems and negative social impact are leading to a point of no return (Carvalho et al., 2013). Therefore, sustainable development is now more important than ever. However, sustainability data is yet to be sufficiently integrated and used for decision making. Chofreh et al. (2014) has proposed a Sustainable Enterprise Resource Planning (S-ERP) system to support the sustainability initiatives. Its information system is driven by sustainability consideration that covers all aspects of the supply chain. *Figure 2-6* below shows the illustration of S-ERP life cycle. As shown in the figure, in order to extend the development of S-ERP system, the development of Cloud S-ERP might be a potential research direction in the future.

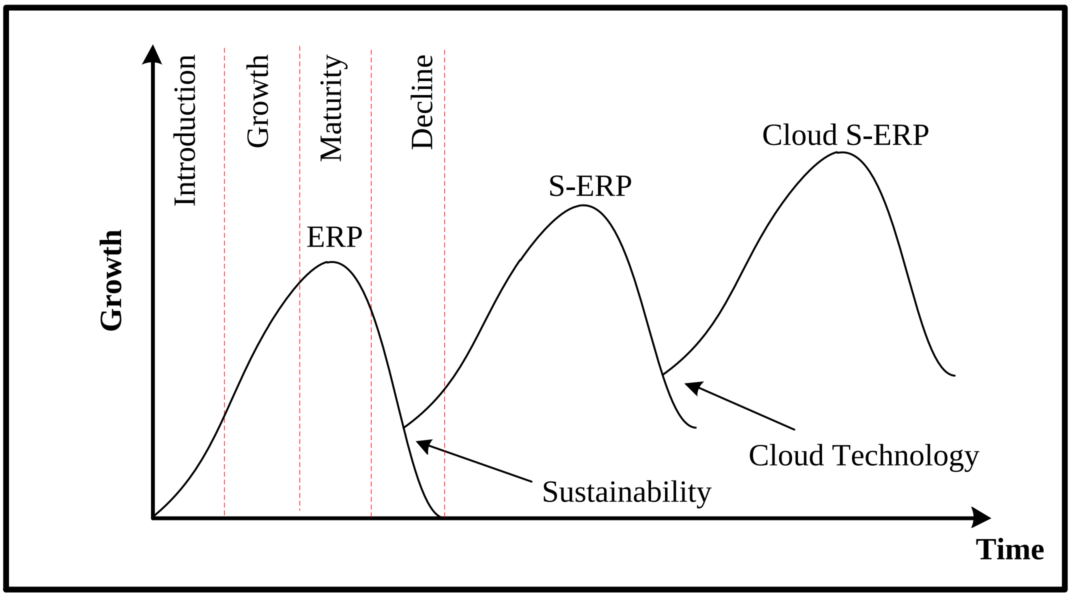

Figure 2-6: The life cycle of S-ERP (Chofreh et al., 2014)

With all the available synthesis and optimisation techniques in addressing supply chain problem reviewed, the research gaps are identified and discussed in the following section.

2.6 Conclusion

As a country with active agricultural activities, Malaysia is blessed with abundant biomass resources that are beneficial to the local economics. To harness the potential of biomass industry, the entire biomass supply chain system must play a critical role. Thus, there is a need for a novel approach to design an integrated biomass supply chain in both urban and rural areas. Despite the contribution of the works reviewed in Section 2.1 – 2.5, several research gaps are noted in current biomass supply chain models below.

Firstly, there are plenty of potential biomass resources in Malaysia which are yet to receive attention and considered in current supply chain system, as discussed in Section 2.1. Furthermore, conventional design of biomass supply chain is limited to only a single type of biomass that considers the conversion processes for a single biomass, rendering less effectiveness. Having multiple types of biomass in a supply chain increases the possibilities of integration between the conversion processes of these resources. In multiple biomass supply chain, energy generated from high energy content biomass can be utilised in the processing of low energy content biomass. The integration of unutilised biomass into the current supply chain system will improve the energy its efficiency and resources conservation.

Secondly, it is worth nothing that the structure of centralisation and decentralisation in biomass supply chains have received limited attention. According to literature, a centralised approach to convention supply chain is frequently proposed to reduce the overall management effort and cost. However, a decentralised approach is preferred for biomass supply chain due to its shelf life and transport density. In practice, no supply chain can be completely centralised or decentralised. Both structures have their advantages and disadvantages. Therefore, there is a need for a systematic approach to determine the overall structure of a biomass supply chain.

Thirdly, biomass utilisation in rural and remote area has not been explored and studied. Previous works often focus on the utilisation of biomass in urban and developed area with well-established transportation facility and infrastructure. As mentioned in Section 2.1, there are numerous sago plantation and mills in rural regions of Sarawak. Although sago waste is an appealing substitute for energy production, it is not fully utilised due to limited transportation structures in Sarawak. Inland waterway by rivers, canals and lakes appears to be a solution to the accessibility of these laid-back areas. Hence, a novel approach to address the logistic issue of the supply chain in rural region is needed.

Fourthly, existing biomass supply chain evaluation tools are not systematic and comprehensive. Economic, environmental and social impact are important aspects in designing supply chain system as they allow decision makers to determine if the proposed designs are sustainable and beneficial to all stakeholders involved. However, different stakeholders (i.e. researcher, investor, industry player or policy maker) have different expectations on all these aspects. Moreover, stakeholders from different regions (i.e. urban or rural) prioritise factors differently regarding decision-making in supply chain design. As a result, it is necessary to capture all the opinions in prioritising each factor in the evaluation of the sustainability of supply chain.

Lastly, most of the supply chain models focus on economic optimisation, which is insufficient – despite boosting economy, biomass supply chain leaves negative impact on the environment and society. Contradicting objectives should be satisfied in optimisation to ensure a sustainable operation. To date, none of the proposed models has been able to capture all these aspects of biomass supply chain processes, considering the broad spectrum of a supply chain. These highlighted gaps serve as motivation for this research work. To compromise the dilemma between model complexity and reality, a model builder should define the scope of the supply chain model in such a way that it is reflective of key real-world dimensions, yet not too complicated to solve. To address these research gaps, research scopes and methodology are proposed in Chapter 3.

CHAPTER 3

RESEARCH SCOPE AND METHODOLOGY

3.1 Research Scope

The motivation of this research work is to address the gap identified in the development of biomass-to-bioproducts supply chain, particularly on the synthesis of multiple biomass supply in both urban and rural areas. To do so, this research work is organised into following scopes:

i. Synthesis and optimisation of biomass supply chain based on multiple biomass corridor (MBC) concept

   Multiple biomass corridor (MBC) concept is introduced to integrate unutilised biomass into existing biomass supply chains. Potential biomass types and their respective processing technologies are identified and incorporated to diversify the current supply chain system. A mathematical model based on MBC concept will be developed to develop a multiple biomass supply chain in Malaysia.

ii. Development of P-graph aided Decomposition approach (PADA) to determine the structure of biomass supply chain

   Logistic network and infrastructure are greatly affected by the characteristics of biomass (i.e. transport density and shelf life) and economic factors (i.e. cost of logistics and processing facility.). The decision of centralising or decentralising processing facilities is critical to ensure the optimum quality of biomass and the economic performance of the supply chain. Therefore, a novel framework is proposed to determine the optimum structure of biomass supply network.

iii. Introduction of resources integrated network (RIN) for the synthesis of biomass supply chain in rural and remote region

Abundance of bioresources in rural area is one of the potential sources of income in local economic development and growth. It has always been challenging to mobilise not only these biomass resources but also the rural community's daily needs due to limited transport infrastructure. Hence, a systematic approach is developed to design and synthesise a biomass supply chain that incorporates bioresources, commodity and inland water transport.

iv. Sustainability analysis and assessment of biomass supply chain based on fuzzy analytical network process (FANP)

The terminology of sustainability has been more familiar in each area of development and is one of the main focuses in research. However, stakeholders in a supply chain system have different concerns in achieving sustainability. With global sustainability in mind, a sustainability standard is generated based on FANP approach to capture different opinions to assess and analyse the economic, environmental and societal impact to society qualitatively.

v. Development of FANP-aided multiple objective optimisation approach for the synthesis of sustainable biomass supply chain

Supply chain optimisation often involves more than one objective function. However, these objectives appear to be conflicting among each other and no single solution exists that simultaneously satisfies all objectives. In this case, a multiple objective optimisation approach is developed to design a biomass supply chain that fulfils sustainability objectives.

In order to explore these scopes, the methodology for this work is discusses in Section 3.2.

3.2 Research Methodology

The proposed research scopes are explore based on a research methodology as shown in *Figure 3-1*. Firstly, an intensive literature review is conducted to identify the research gaps of current work on biomass supply chain synthesis and optimisation. Besides, data is also collected at this stage and it serves as an input to the case study of the work later. The summary of the literature review is provided in Chapter 2. Based on the research gaps identified, the research scopes and methodology are defined in Chapter 3.

In Chapter 4, multiple biomass corridor (MBC) concept is introduced to incorporate multiple unutilised biomass types and their respective processing technologies into the current biomass system in urban and developed regions. To synthesise a sustainable biomass supply chain based on MBC, a generic super structure is first developed, consisting of multiple biomass supplies, biorefineries with available processing technologies and bioproduct demands. Based on the developed structure, a mathematical model of MBC is developed to determine the optimum logistic network, technology network and biorefinery location.

Chapter 4 is then extended in Chapter 5 to consider the structure of the biomass supply chain system, whether centralised or decentralised. A P-graph aided decomposition approach (PADA) is proposed to break the complex supply chain synthesis model into two simplified sequential sub-models: (i) biomass conversion technology selection and (ii) biomass allocation and processing hub selection. The former is solved first by the conventional mathematical model developed in Chapter 4 to generate an optimum biomass processing network, whereas the latter is solved using P-graph approach to determine the type of supply chain network.

For the development of biomass supply chain in rural and remote areas, resources integrated network (RIN) is proposed in Chapter 6. It includes bioresources and food commodities produced by respective rural villages as well as the rural community's daily needs into the supply chain system to improve its efficiency and the overall rural economy. The network starts from delivering the rural community's needs from depot to respective demands and collecting bioresources from these demands simultaneously. This part will be modelled as a vehicle routing problem (VRP). The bioresources are then transported to each processing mill to be processed into corresponding biomass and products. Multiple biomass corridor model will be extended by incorporating bioresources to simulate the second part. Due to limited transport infrastructure in remote regions, inland water transport is expected to be the primary mode of transportation.

Next, Chapter 7 presents a systematic framework based on fuzzy analytical network process (FANP) to assess and analyse biomass supply chain in terms of economic, environmental and social factors. Two groups of stakeholders along the supply chain: (i) stakeholders from West Malaysia representing urban communities and (ii) stakeholders from East Malaysia representing rural communities are invited to response to a questionnaire on the level of dominance relationship between different sustainability factors. The final priority weightage is integrated with respective sustainable factors to form a sustainability index, which can be adopted to assess the sustainability of biomass supply chain quantitatively. The differences between the sustainability indices of urban and rural community are compared and analysed.

Following Chapter 7, the sustainability index obtained is coupled with MBC model to form a multiple objective optimisation model. This fuzzy analytical network process (FANP) based optimisation model is proposed to synthesise a sustainable supply chain based on the economic, environmental and social criteria provided by different stakeholders involved along the value chain. To demonstrate this framework, a case study based at Johor state is solved. Lastly, conclusion and future works are drawn in Chapter 9.

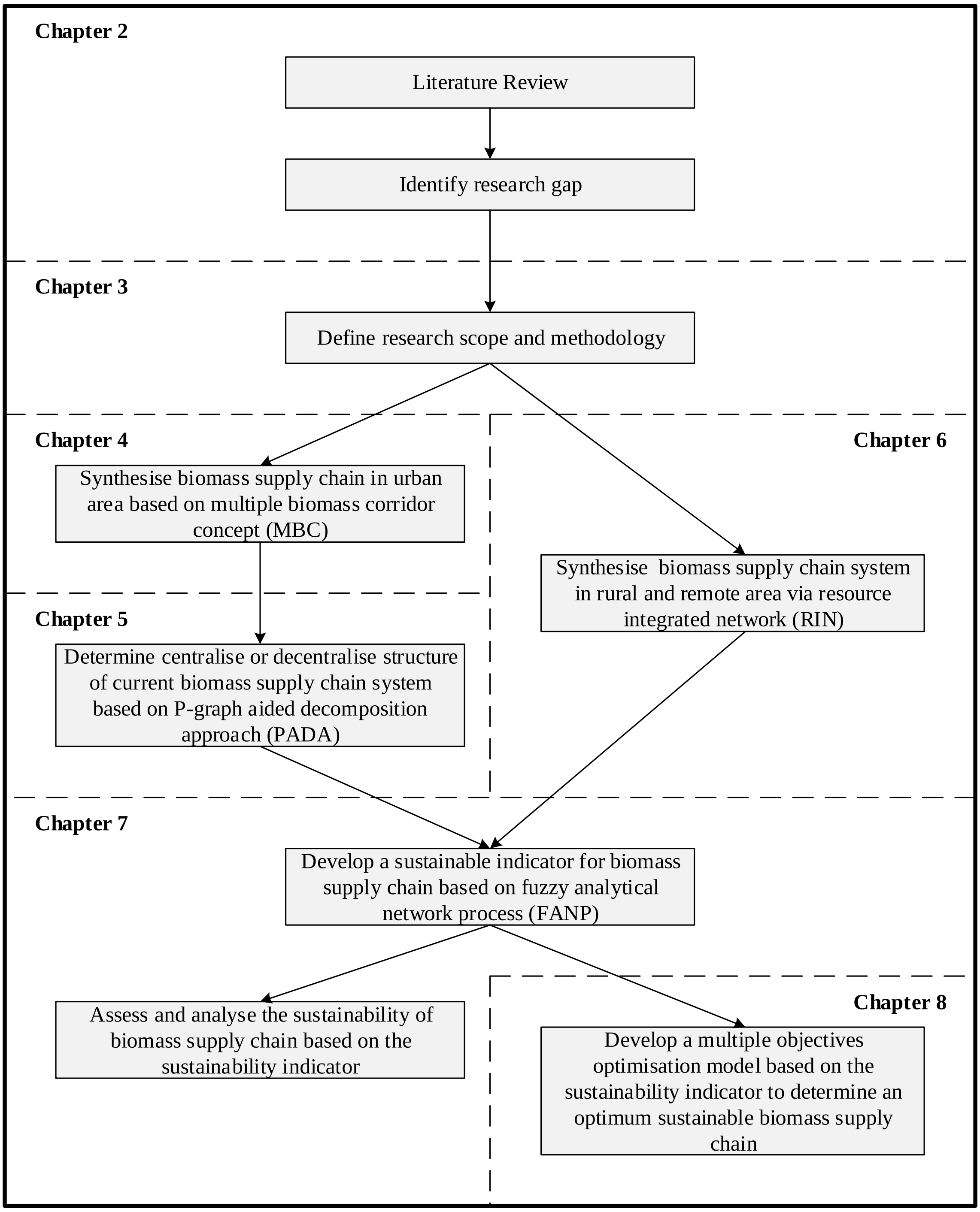

Figure 3-1: Research methodology

CHAPTER 4

ENCHANCED GREEN ECONOMY OF URBAN AND DEVELOPED REGION VIA MULTIPLE BIOMASS CORRIDOR (MBC)

4.1 Introduction

As discussed previously, mushrooming population growth has led to drastic exploitation of finite fossil fuels. Along with its detrimental effects on the environment, such practice is now deemed unsustainable. Due to increasing population, the current global agricultural production needs to increase by 70-110% to meet the demand in 2050 (Tilman et al., 2011). Gigantic amount of agricultural wastes generated from such practice will result in waste management issues. As a result, this phenomenon has led to the interest in biomass utilisation in energy and chemical productions. This waste-to-wealth strategy is no doubt highly beneficial to the society, promoting global sustainability development. Multiple unutilised wastes are to be recovered and utilised instead of being incinerated or buried, thus encouraging the utilisation of biomass globally in line with a systematic design of an integrated supply chain. This in turn increases the local green economy through the development of local biomass and biorefinery industry. However, only 10% of biomass resources are fully utilised (Alakangas et al., 2012). Among these unnoticed biomass resources, some are very promising substitutes for fossil fuel.

Therefore, this chapter proposes a multiple biomass corridor (MBC) concept to integrate multiple biomass resources, especially those unutilised in current supply chain systems. The concept clusters the allocation of biomass resources, biomass processing and the final delivery of value-added product as a supply chain system as shown in *Figure 4-1*. Systematic approach will be proposed based on the concept for the formulation of an optimum supply and demand network with optimum hubs and technologies selected. An actual case study in Malaysia will be developed to illustrate this green concept.

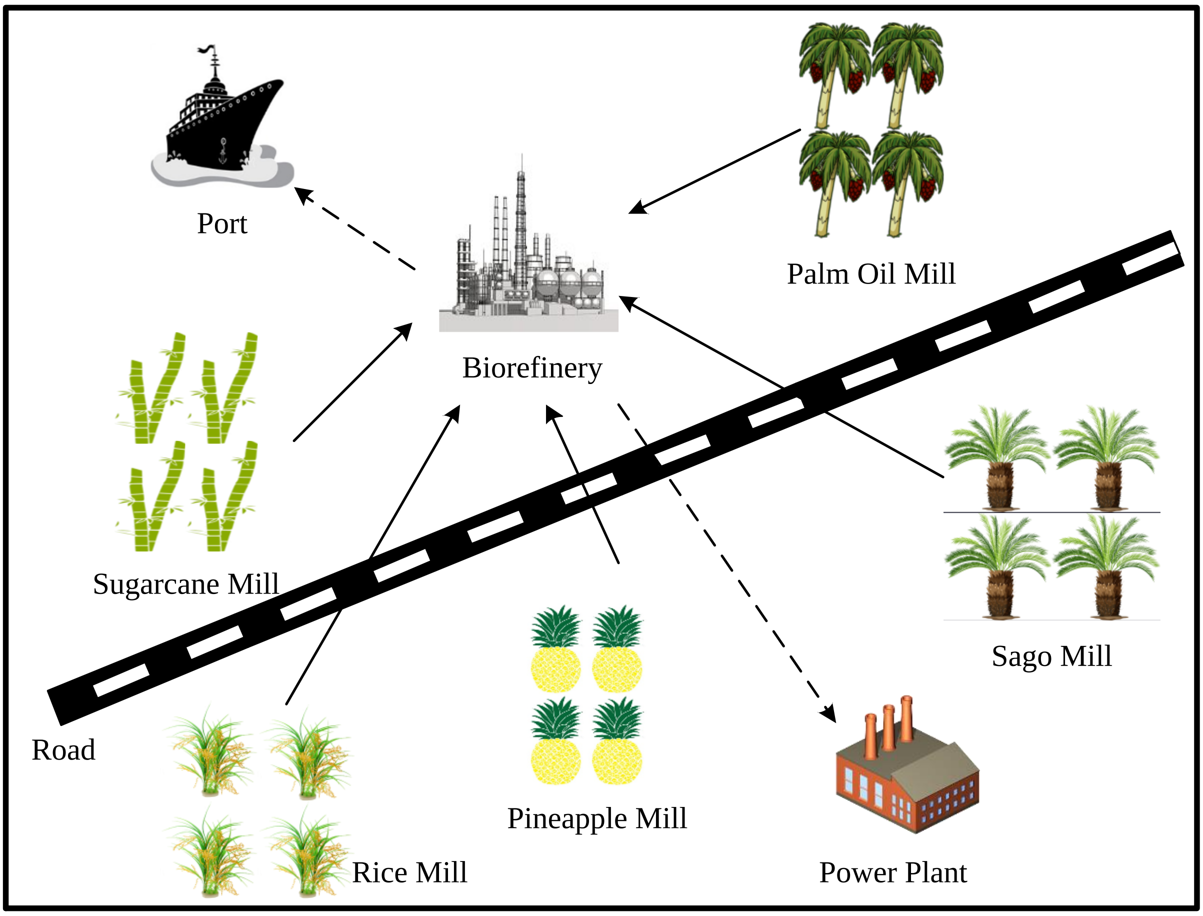

Figure 4-1: Multiple biomass corridor (MBC)

4.2 Problem Statement

As various potential biomass resources with different processing technologies are available, the synthesis of an integrated biomass supply chain is a highly complex problem. A generic representation of the problem is shown in *Figure 4-2*.

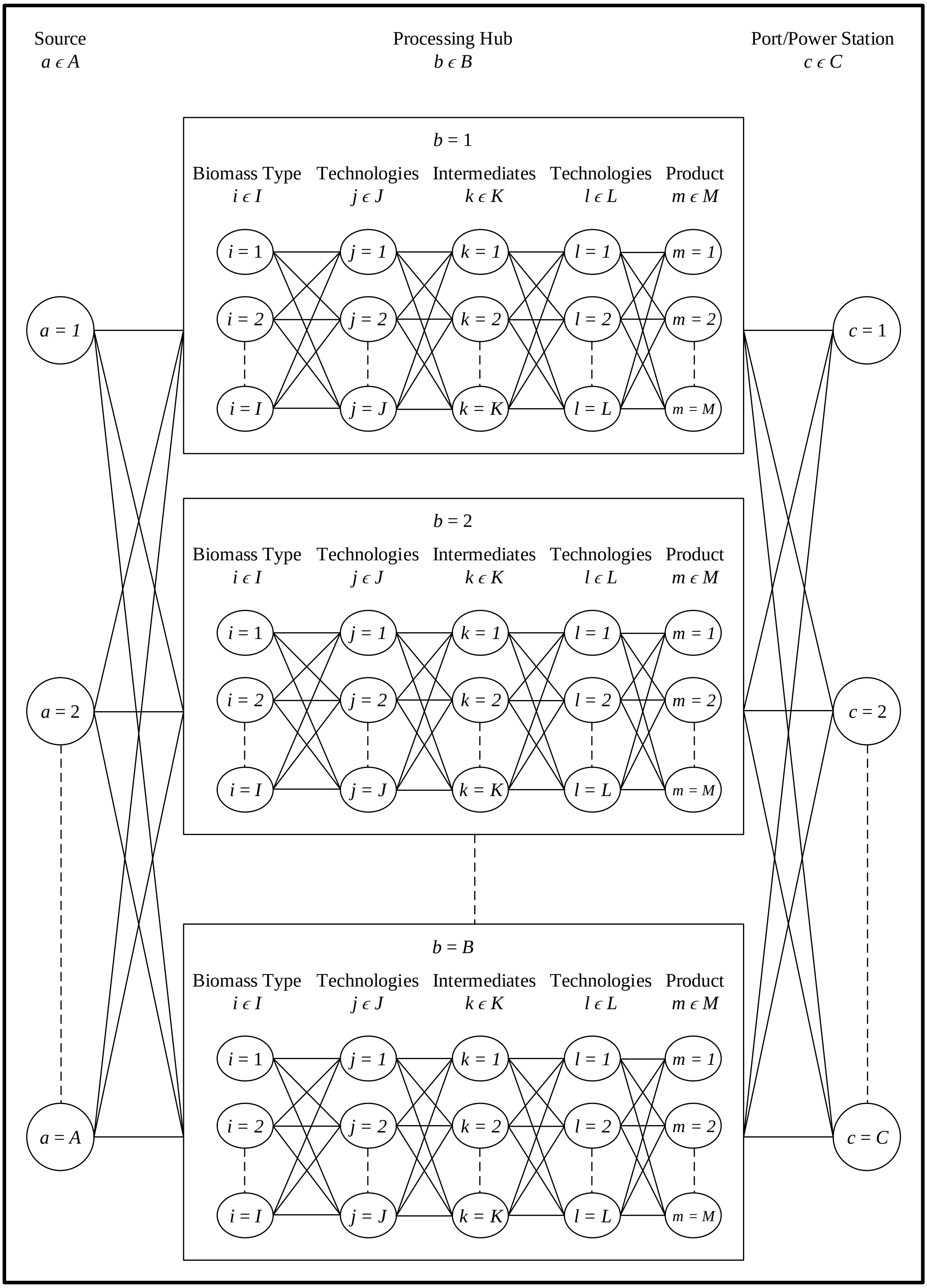

Figure 4-2: Superstructure of an integrated biomass supply chain

The synthesis problem to be addressed is formally stated as follows: a set of biomass sources $a \in A$ with availability, Z_a that is to be allocated to a set of integrated processing hub $b \in B$ with capacity Z_b and the final product is to be sent to a set of ports or power plants $c \in C$ with demand Z_c. In the processing hub, biomass type $i \in I$ is converted to intermediate $k \in K$ through technology $j \in J$ and finally converted to product $m \in M$ via technology $l \in L$. Besides, energy (i.e. electricity and steam) $e \in E$ can be produced from biomass type i and intermediate k via technology j and l to sustain the process or to be exported. To determine an optimum biomass supply chain, a systematic approach based on MBC is proposed in this work. The following section further explains the methodology developed for this work.

4.3 Methodology

The comprehensive methodology based on MBC to solve biomass supply chain synthesis problem is presented in *Figure 4-3*. As shown, a list of potential biomass resources is first identified. In the second step, the processing technologies of the identified biomass types are determined. With the locations of supply, potential processing hub and demand discovered, the superstructure of the synthesis problem is constructed based on *Figure 4-2*. Mathematical formulation based on the superstructure generated is developed with objective functions specified. Next, the relevant information (e.g. biomass availability, distance between sources, hubs and demand, cost etc) is gathered and inputted into the optimisation model. The model is then solved to determine the optimum logistic network with hub location and optimum biorefinery structure based on the objective functions predefined. The following section further explains the parameters and variables involved in the mathematical formulation. Besides, the equations formulated in the optimisation model are also clearly presented and described methodically to address an integrated biomass supply chain synthesis problem.

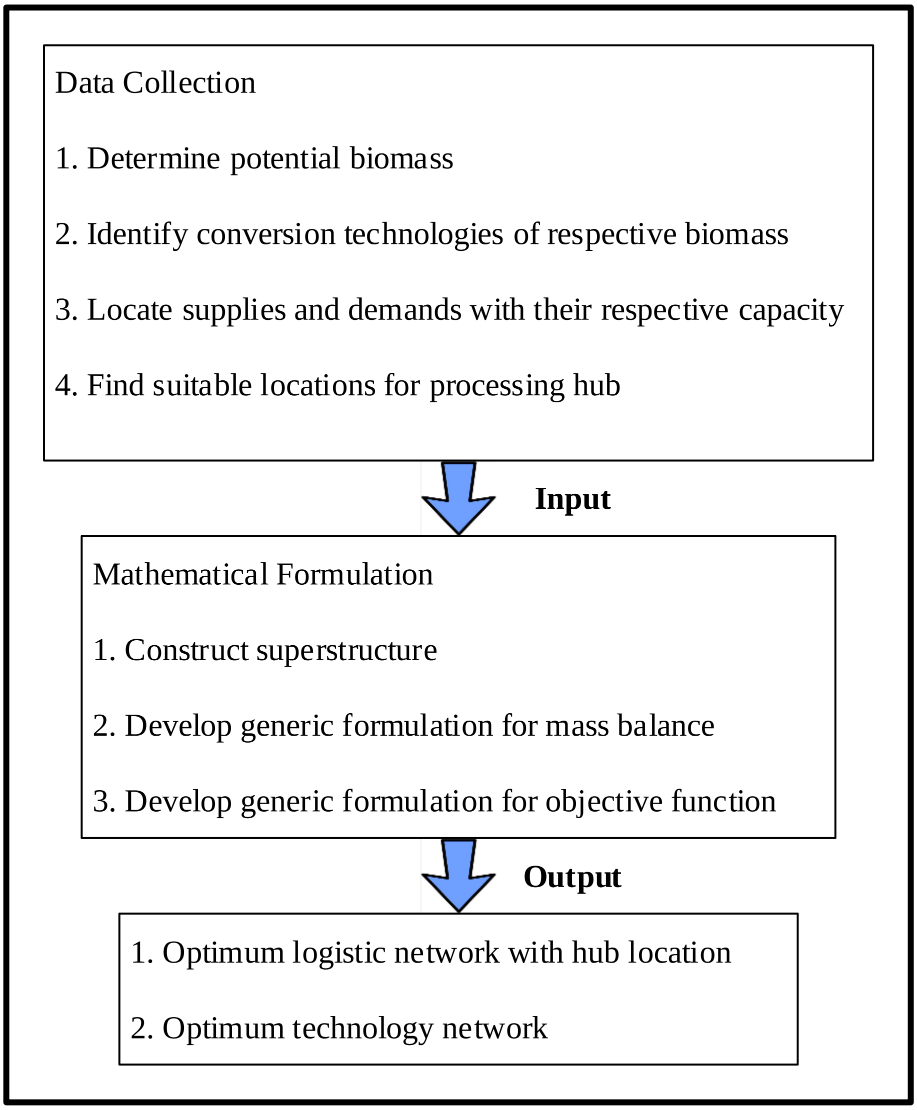

Figure 4-3: Methodology for multiple biomass corridor (MBC)

4.4 Model Formulation

In this model, an integrated biomass supply chain synthesis problem is solved sequentially from biomass allocation to technology selection and product distribution. It is capable of accounting for multiple biomass types and processing technologies, synthesising an optimum supply and demand network. Based on *Figure 4-3*, the detailed formulation of the proposed MBC model is presented from Section 4.3.1 to Section 4.3.3.

4.4.1 Material Flow

In the supply chain network, the biomass is first transported from source *a* to hub *b* to be processed to value-added products. The total biomass delivered from source *a* to hub *b* is constrained by the biomass available at *a* and the capacity of hub *b*.

$$\mathrm{CA}_a \geq \sum_{b \in B} F_{a,b} \qquad \forall a \in A \tag{4.1}$$

$$\mathrm{CA}_b \geq \sum_{b \in B} F_{a,b} \qquad \forall b \in B \tag{4.2}$$

where CA_a is the amount availability of biomass at source *a*; CA_b is the capacity of processing hub *b*; $F_{a,b}$ is the amount of biomass flow from source *a* to hub *b*.

The selection of potential processing hubs can be determined by the following constraints. Note that β_b is a binary variable which denotes the selection of hub *b* (value of "1" indicates that the hub is selected, else "0") while $\mathrm{Hub}^{\mathrm{N}}$ refers to the number of hubs required which can be predefined.

$$\sum_{b \in B} \sum_{a \in A} F_{a,b} = \sum_{b \in B} \sum_{a \in A} (\beta_b \mathrm{CA}_a) \qquad \forall b \in B \tag{4.3}$$

$$\sum_{b \in B} \beta_b = \mathrm{Hub}^{\mathrm{N}} \tag{4.4}$$

All the processing hubs are assumed to be identical (i.e. integrated with all the technologies available). The total biomass from source *a* to hub *b* will be equal to the available biomass feedstock in hub *b*. In the integrated processing hub *b*, the available biomass feedstock is equal to the total biomass of type *i*.

$$\sum_{a \in A} F_{a,b} = F_{b,in} \qquad \forall b \in B \qquad (4.5)$$

$$F_{b,in} = \sum_{i \in I} F_i^b \qquad \forall b \in B \qquad (4.6)$$

where $F_{b,in}$ represents the available biomass in hub b, F_i^b is the amount of biomass type i.

Biomass type i is then transferred to technology j to be converted to intermediate k.

$$F_i^b = \sum_{j \in J} F_{i,j}^b \qquad \forall i \in I, \forall b \in B \qquad (4.7)$$

$$F_k^b = \sum_{j \in J} \sum_{i \in I} \left(F_{i,j}^b \mathrm{CR}_{j,k} \right) \qquad \forall k \in K, \forall b \in B \qquad (4.8)$$

where $F_{i,j}^b$ is the amount of biomass i sent to technology j; F_k^b is the amount of intermediate k; $\mathrm{CR}_{j,k}$ is the conversion rate of technology j converting biomass i to intermediate k.

The intermediate k is then further processed and converted into final product m via technology l.

$$F_k^b = \sum_{l \in L} F_{k,l}^b \qquad \forall k \in K, \forall b \in B \qquad (4.9)$$

$$F_m^b = \sum_{l \in L} \sum_{k \in K} \left(F_{k,l}^b \mathrm{CR}_{l,m} \right) \qquad \forall m \in M, \forall b \in B \qquad (4.10)$$

where $F_{k,l}^b$ denotes the amount of intermediate k sent to technology l; F_m^b is the amount of product m; $\mathrm{CR}_{l,m}$ is the conversion rate of technology l converting intermediate k to product m.

Energy is generated from both biomass i and intermediate k via technology j and l to sustain the plant operation. Excess or shortage of energy can be exported and imported respectively.

$$F_{e,GEN}^{b} = \sum_{j\in J}\sum_{i\in I}\left(F_i^b \mathrm{CR}_{\mathrm{j,e}}\right) + \sum_{l\in L}\sum_{k\in K}\left(F_k^b \mathrm{CR}_{l,e}\right) \qquad \forall e \in E, \forall b \in B \qquad (4.11)$$

$$F_{e,CON}^{b} = \sum_{j\in J}\sum_{k\in K}\left(F_k^b \mathrm{CE}_{e,j}\right) + \sum_{l\in I}\sum_{m\in M}\left(F_m^b \mathrm{CE}_{e,l}\right) \qquad \forall e \in E, \forall b \in B \qquad (4.12)$$

$$F_{e,CON}^{b} = F_{e,GEN}^{b} + F_{e,IM}^{b} - F_{e,EX}^{b} \qquad \forall e \in E, \forall b \in B \qquad (4.13)$$

where $F_{e,CON}^{b}$, $F_{e,GEN}^{b}$, $F_{e,IM}^{b}$, $F_{e,EX}^{b}$ is the amount of energy consumed, generated, import and export respectively in hub *b*; $\mathrm{CR}_{j,e}$ and $\mathrm{CR}_{l,e}$ is the conversion rate for energy generation from biomass *i* and intermediate *k* respectively; $\mathrm{CE}_{e,j}$ and $\mathrm{CE}_{e,l}$ is the energy consumed per unit of product of technologies *j* and *l*.

The total product produced in hub *b* is equal to the product output of hub *b*. At the last stage, the product output of hub *b* is to be sent respective ports and power stations. The product delivery is constrained by the demand capacity.

$$\sum_{m\in M} F_m^b = F_{b,out} \qquad \forall b \in B \qquad (4.14)$$

$$F_{b,out} = \sum_{c\in C} F_{b,c} \qquad \forall b \in B \qquad (4.15)$$

$$\mathrm{CA}_c \geq \sum_{c\in C} F_{b,c} \qquad \forall c \in C \qquad (4.16)$$

where $F_{b,out}$ denotes the product output of hub *b*; $F_{b,c}$ represents the amount of product transported from processing hub *b* to port/power station *c*; CA_c is the capacity of demand.

4.4.2 Economic Performance Evaluation

In this work, annualised gross profit (AC^{GP}) is used to evaluate the economic performance of the supply chain. The AC^{GP} of a supply chain can be defined as the difference between annual revenue (AC^{RE}), annual production cost (AC^{PR}), annual transportation cost (AC^{TR}) and annual hub investment cost (AC^{IN}).

$$AC^{GP} = AC^{RE} - AC^{PR} - AC^{TR} - AC^{IN} \tag{4.17}$$

The AC^{RE}, AC^{PR}, and AC^{TR} of products can be calculated as follows:

$$AC^{RE} = \sum_{b\in B}\left(\sum_{m\in M} F_m\,\mathrm{SC}_m + \sum_{e\in E} E_{EX}\,\mathrm{SC}_e\right) \tag{4.18}$$

$$\begin{aligned} AC^{PR} = \sum_{b\in B}\Bigg(&\sum_{i\in I} F_i\,\mathrm{BC}_i + \sum_{e\in E} F_{e,IM}^{b}\,\mathrm{BC}_e + \sum_{k\in K}\sum_{j\in J}\left(F_k \mathrm{CC}_j\right) + \sum_{m\in M}\sum_{l\in L}\left(F_m \mathrm{CC}_l\right) \\ &+ \sum_{k\in K}\sum_{j\in J}\left(F_k \mathrm{OC}_j\right) + \sum_{m\in M}\sum_{l\in L}\left(F_m \mathrm{OC}_l\right)\Bigg) \end{aligned} \tag{4.19}$$

$$AC^{TR} = \sum_{a\in A}\sum_{b\in B}\left(F_{a,b}\left(\mathrm{FC}\times \mathrm{D}_{a,b} + \mathrm{HC}\right)\right) + \sum_{b\in B}\sum_{c\in C}\left(F_{b,c}\left(\mathrm{FC}\times \mathrm{D}_{b,c} + \mathrm{HC}\right)\right) \tag{4.20}$$

where FC denotes transportation cost; $D_{a,b}$ and $D_{b,c}$ represents the distance travelled from source *a* to hub *b* and from hub *b* to demand *c* respectively; HC is the handling cost; SC and BC denotes the respective selling price and buying cost; CC and OC represents capital cost and operating cost accordingly.

AC^{IN} refers to the annual capital cost required to set up a processing hub. The total capital cost is first calculated by the submission of construction cost and land cost (C^{Con} and C^{Land}) of each of the processing hubs. Capital recovery factor (CRF) is then included to convert the total capital cost to annualised capital cost for a given length of time (i.e. lifespan of the processing hub, LS) at a specified interest rate (RI).

$$AC^{IN} = \sum_{b\in B} \beta_b \times \left(\mathrm{C}^{\mathrm{Con}} + \mathrm{C}^{\mathrm{Land}}\right) \times \mathrm{CFR} \tag{4.21}$$

$$\mathrm{CRF} = \frac{\mathrm{RI}(1+\mathrm{RI})^{\mathrm{LS}}}{(1+\mathrm{RI})^{\mathrm{LS}}-1} \tag{4.22}$$

4.4.3 Objective Function

The optimum supply chain structure can be determined by maximising AC^{GP}. Hence, the objective function can be defined as follows:

$$Maximise\ AC^{GP} \tag{4.23}$$

A case study is then presented in the next section to demonstrate this proposed approach.

4.4 Case Study

As Malaysia is bestowed with significant amount of biomass resources, the MBC concept can act as a systematic step-by-step guideline to the development of an integrated biomass supply chain ecosystem. The advancement of biomass industry reduces the waste management issues within the country. At the same time, it positions the country as an international biomass hub, driving a growth in the green economy. In this respect, this case study presents the synthesis and design of an integrated biomass supply chain in the state of Johor in Peninsular Malaysia via the proposed framework. As discussed in Section 2.1, palm oil, pineapple, sugarcane and paddy biomass are identified as the potential biomass for energy and chemical generation in Malaysia. In this case study, a total of 25 sources of biomass supplied within the state are considered; their location and availability are tabulated in *Table 4-1*. Biomass is first transported to a single centralised hub that is to be chosen from 5 potential candidates. The location and the capacity of each processing hubs is shown in *Table 4-2*. The mode of bulk transportation of biomass is truck and the distanced travelled is obtained from Google Map.

Table 4-1: The location and the availability of biomass sources

Source	Latitude	Longitude	Amount (t/y)	Source	Latitude	Longitude	Amount (t/y)
a_1	2.3512	102.6248	1,550	a_{14}	1.5215	103.4639	200
a_2	2.4132	103.8532	10	a_{15}	2.0255	103.3616	1,174,300
a_3	2.0418	102.5928	3,550	a_{16}	1.6667	103.5511	939,400
a_4	2.0255	103.3616	50	a_{17}	1.7826	103.9339	352,200
a_5	1.5234	103.6130	460	a_{18}	1.9916	102.8375	1,051,400
a_6	2.5350	102.7988	270	a_{19}	1.9057	103.3789	469,700
a_7	1.6667	103.5511	240	a_{20}	1.6074	103.6666	704,500
a_8	1.7826	103.9339	100	a_{21}	2.3512	102.6248	2,770
a_9	2.3512	102.6248	560	a_{22}	2.4132	103.8532	2,610
a_{10}	2.0418	102.5928	670	a_{23}	2.0418	102.5928	1,600
a_{11}	2.0255	103.3616	320	a_{24}	2.0255	103.3616	380
a_{12}	2.5350	102.7988	1,540	a_{25}	1.9916	102.8375	350
a_{13}	1.7826	103.9339	170				

Sugar cane (a_1- a_8); pineapple (a_9-a_{14}); palm oil (a_{15}- a_{20}); paddy (a_{21}- a_{25})

Table 4-2: The location and capacity of potential processing hubs

Hub	Latitude	Longitude	Capacity (t/y)
b_1	2.3790	103.8500	4,750,500
b_2	1.9149	103.1885	5,530,800
b_3	1.7961	103.3349	4,832,000
b_4	1.6349	103.6036	5,177,000
b_5	1.4482	103.8941	4,950,900

For the processing hub, available biomass conversion technologies are identified for the construction of superstructure as presented in *Figure 4-4*. It is assumed that the "super" hub contains all the technologies available and it acts as warehouse storage for both the raw materials and products.

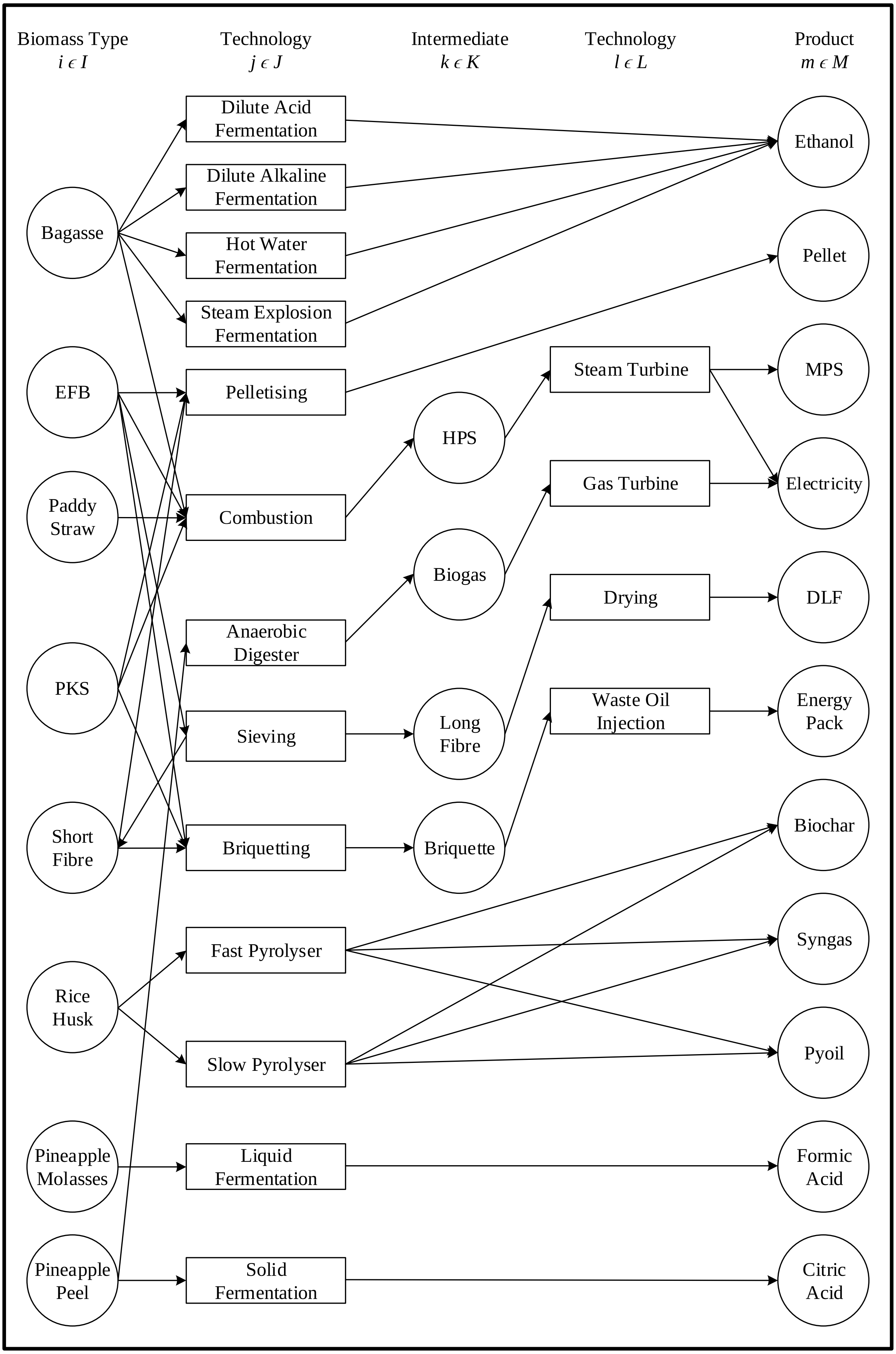

Figure 4-4: Superstructure of the case study

As shown in *Figure 4-4*, sugarcane bagasse first undergoes dilute acid, dilute alkaline, hot water or steam explosion pre-treatment to increase product yield prior to ethanol fermentation. Pineapple biomass which consists of solid and liquid can be converted into organic acid (i.e. citric and formic acid) via solid and liquid fermentation respectively. The organic-rich pineapple peel can be utilised for biogas generation in an anaerobic digester (Chau & David, 1995). From the processing of EFB into value-added products, short fibre and long fibre is produced. Long fibre can be dried and stored as a good source of energy. Meanwhile, short fibre and PKS can be further processed to value-added products through pelletising or briquetting process. It is assumed that all waste motor oil available will be injected into briquette to produce energy pack. The ratio of waste motor oil to briquette weight ratio is 0.15:1 (Ng et al., 2014). Alternatively, these oil palm biomasses can be directly combusted to high pressure steam. Generated high pressure steam can be used to generate electricity and medium pressure steam in the turbine to sustain the energy usage of the biorefinery. Additional utility generated is marketable. Similarly, both sugar cane bagasse and paddy straw are good sources for energy synthesis. Lastly, high-energy-content rice husk can be converted into biochar, syngas and biooil through pyrolysis (Tsai et al., 2007). The conversion rates of these technologies are tabulated in *Table 4-3*.

Table 4-3: Multiple processing technologies with their respective conversion

Technology	**Product**	**Conversion Factor**
Boiler	High pressure steam	3.83 t/t paddy straw[5]
		2.59 t/t empty fruit brunches[1]
		3.95 t/t palm kernel shell[1]
		2.2 t/t bagasse[2]
Steam Turbine	Electricity	0.58 Kw/t high pressure steam[1]
	Medium pressure steam	0.91 t/t high pressure steam[1]
Dehydration	Dried long fibre	0.56 t/t wet long fibre[1]

Table 4-3 (cont'): Multiple processing technologies with their respective conversion

Technology	Product	Conversion Factor
Separation and sieving	Wet short fibre	0.24 t/t empty fruit brunches[1]
	Wet long fibre	0.67 t/t empty fruit brunches[1]
Gas turbine	Electricity	1.05 Kw/t biogas[2]
Pelletising	Pellet	0.33 t/t wet short fibre[1]
		0.33 t/t palm kernel shell[1]
Briquetting	Briquette	0.33 t/t wet short fibre[1]
		0.33 t/t palm kernel shell[1]
Waste oil injection	Energy pack	1.15 t/t briquette[1]
Acid fermentation	Bioethanol	250 L/t bagasse[3]
Alkaline fermentation	Bioethanol	260 L/t bagasse[3]
Hot water fermentation	Bioethanol	255 L/t bagasse[3]
Steam fermentation	Bioethanol	230 L/t bagasse[3]
Solid fermentation	Citric acid	0.9 t/t pineapple peel[4]
Liquid fermentation	Formic acid	0.79 t/t pineapple peel[4]
Fast pyrolyser	Biochar	0.26 t/rice husk[5]
	Syngas	210 L/t rice husk[5]
	Biooil	530 L/t rice husk[5]
Slow pyrolyser	Biochar	0.36 t/rice husk[5]
	Syngas	640 L/t rice husk[5]
	Biooil	299 L/t rice husk[5]
Anaerobic digester	Biogas	0.36 t/t pineapple peel[6]

[1]Lam et al. (2013); [2]Munir et al. (2014); [3]Kumar and Murthy (2012); [4]Chau and David (1995); [5]Brownsort (2009); [6]Chulalaksananukul et al. (2012)

The operating and capital cost of technologies are summarised in *Table 4-4* while their respective energy consumption is presented in *Table 4-5*. The final products are assumed to be send to Johor Port for exportation. Note that the raw material, product and utility costs adopted from research and commercial statistics are listed in *Table 4-6*.

Table 4-4: The operation and capital cost of respective technologies

Technology	Capital Cost (per product)	Operating Cost (per product)
Boiler[1]	2.40 USD/t	0.20 USD/t
Steam Turbine[1]	0.05 USD/Kw	0.05 USD/Kw
Dehydration[1]	9 USD/t	18.50 USD/t
Pelletising[1]	5 USD/t	22 USD/t
Briquetting[1]	8.5 USD/t	16.5 USD/t
Waste oil injection[1]	2.5 USD/t	10.5 USD/t
Gas Turbine[1]	0.05 USD/Kw	0.05 USD/Kw
Acid fermentation[2]	20.50 USD/t	49.50 USD/t
Alkaline fermentation[2]	26 USD/t	41 USD/t
Hot water fermentation[2]	18 USD/t	25 USD/t
Steam fermentation[2]	17.50 USD/t	22 USD/t
Solid fermentation[3]	120 USD/t	97 USD/t
Liquid fermentation[3]	68 USD/t	110 USD/t
Fast pyrolyser[4]	31 USD/t	59 USD/t
Slow pyrolyser[5]	31 USD/t	36 USD/t
Anaerobic digester[6]	23 USD/t	46 USD/t

[1]Lam et al. (2013); [2]Kumar and Murthy (2012); [3]Vogelbusch (2015); [4]Wright et al (2010); [5]Lehmann & Joseph (2015); [6]Weersink & Mallon (2007)

Table 4-5: Energy consumption for each technology

Technology	Electricity Consumption (per product)	Steam Consumption (per product)
Dehydration[1]	220 Kw/t	2.8 MPS/t
Pelletising[1]	180 Kw/t	3.0 MPS/t
Briquetting[1]	140 Kw/t	2.8 MPS/t
Waste oil injection[1]	30 Kw/t	-
Acid fermentation[2]	140 Kw/t	1.5 MPS/t
Alkaline fermentation[2]	133 Kw/t	1.5 MPS/t
Hot water fermentation[2]	132 Kw/t	1.5 MPS/t
Steam fermentation[2]	133 Kw/t	0.9 MPS/t

Table 4-5 (con't): Energy consumption for each technology

Technology	Electricity Consumption (per product)	Steam Consumption (per product)
Solid fermentation[3]	127 Kw/t	0.6 MPS/t
Liquid fermentation[3]	145 Kw/t	0.1 MPS/t
Fast pyrolyser[4]	90 Kw/t	-
Slow pyrolyser[4]	90 Kw/t	-
Anaerobic digester[5]	120 Kw/t	-

[1]Lam et al. (2013); [2]Kumar and Murthy (2012); [3]Vogelbusch (2015); [4]NCPC (2014); [5]Nayono (2019)

Table 4-6: The price of biomass sources, product and utility

Material	Price	Material	Price
Biomass Feedstock		Final Product	
Empty Fruit Brunches[1]	30 USD/t	Dried Long Fibre[1]	160 USD/t
Palm Kernel Shell[1]	35 USD/t	Palette[1]	140 USD/t
Paddy Straw[2]	20 USD/t	Energy Pack[1]	130 USD/t
Rice Husk[2]	15 USD/t	Biochar[5]	350 USD/t
Bagasse[3]	40 USD/t	Citric Aicd[4]	700 USD/t
Pineapple Peel[4]	25 USD/t	Formic Acid[4]	450 USD/t
Pineapple Molasses[4]	50 USD/t	Bioethanol[6]	0.53 USD/L
Utility		Syngas[7]	0.12 USD/L
Import Electricity[1]	0.14 USD/kWh	Py-oil[8]	0.25 USD/L
Export Electricity[1]	0.11 USD/kWh		
Transportation Cost[1]	0.2 USD/t/km		
Handling Cost[1]	0.5 USD/t		

[1]Lam et al. (2013); [2]Bhattacharyya (2014); [3]Kumar and Murthy (2012); [4]Chau and David (1995); [5]Kulyk (2009), [6]Macrelli et al. (2012); [7]Syntes (2016); [8]EUBIA (2012)

The collected data is then fed as input to solve the mathematical model. The objective function is optimised, and the result is discussed in the following section.

4.5 Result and Discussion

To generate the optimum integrated supply chain for the case study, the developed mathematical model is optimised based on Equation 4.23 subject to Equations 4.14 – 4.22. The mixed-integer linear programming (MILP) model is solved via a commercial optimisation software LINGO v17.0 with Global Solver. The computational time is about 1s and the resulted model has a total of 393 variables and 273 constraints. Based on the solution report, b_4 is selected as the location for the centralised processing hub. The optimum structure of the processing hub is shown in *Figure 4-7.* While the geographical location of biomass sources, potential processing hubs and demand is presented in *Figure 4-5*. *Table 4-7* summarises the optimised costs of the integrated biomass supply chain. The output of the model shows that the production, transportation and hub capital cost account for 48%, 26% and 4% of the total revenue respectively, resulting in a total annual gross profit of 68.85 million USD.

Table 4-7: Model output

Cost	Optimised Result (million USD/y)
Annual Revenue (AC^{RE})	303.71
Annual Production Cost (AC^{PR})	145.49
Annual Transportation Cost (AC^{TR})	79.36
Annual Hub Capital Cost (AC^{IN})	10.00
Annual Gross Profit (AC^{GP})	68.85

The addition of the following constraint into the model allows the selection of a specific location as the processing hub.

$$\beta_b = 1 \tag{4.23}$$

The binary variables, β_b of each of the potential hubs are adjusted to 1 alternately and the AC^{PR} of each of the scenarios is recorded and displayed in *Figure 4-7*.

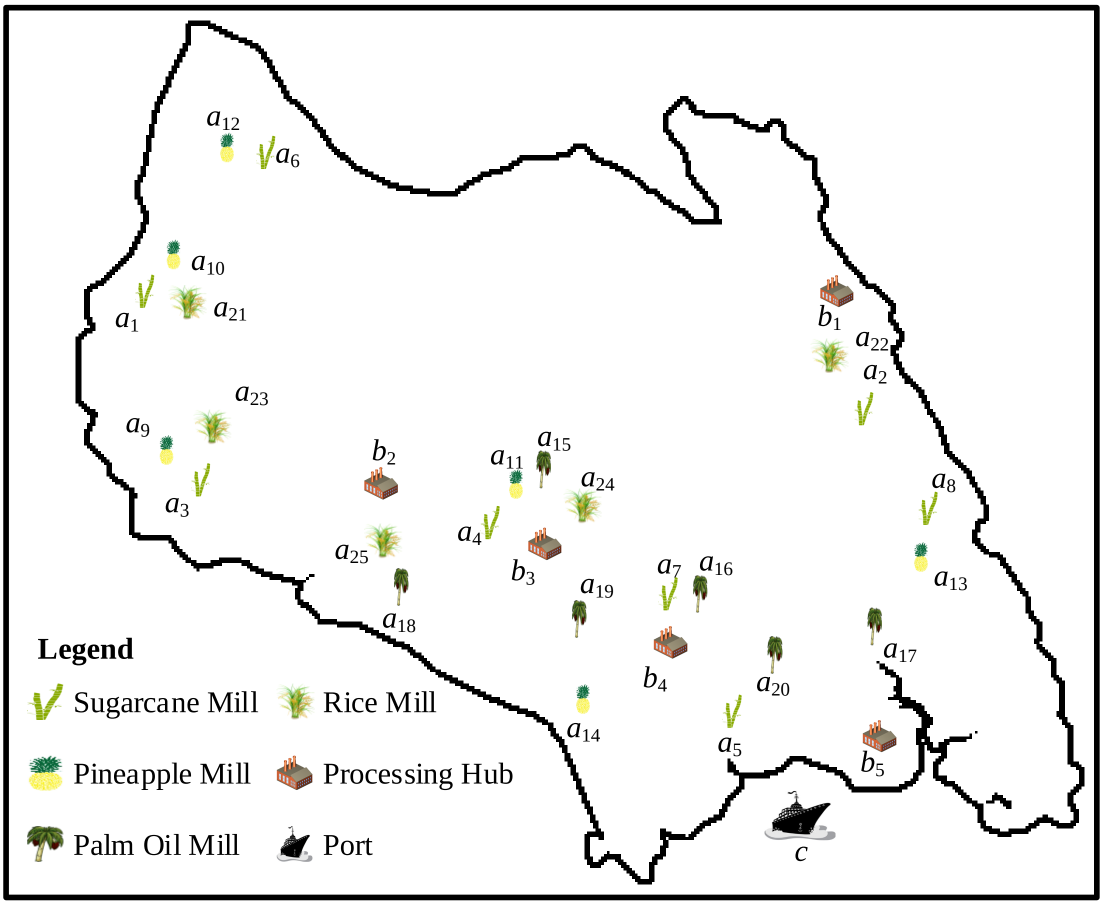

Figure 4-5: Geographical location of each sources, hubs and demand

As shown in *Figure 4-5*, hub b_1 locates furthest from the biomass sources and port. Therefore, selecting of hub b_1 as the centralised processing hub incurs the highest AC^{TP} as observed in *Figure 4-6*. As hub b_5 positions nearest to the port, the cost of product delivery from b_5 to the port is the cheapest. However, the transportation of raw biomass from all the sources to the southernmost facility costs 87.29 million USD annually, resulting in a higher AC^{TP} as compared to hub b_2, b_3, and b_4. Similarly, situating near to majority of the high dense mills does not make b_2 and b_3 the best location for the centralised processing hub. To transport such a huge amount of product, the product delivery cost is equally dominant to the raw material allocation cost in the determination of total transportation cost. Although the biomass transportation to b_4 is higher as compared to b_2 and b_3, the shorter distance between b_4 and port cuts down the total transportation cost, making b_4 the optimum centralised processing hub.

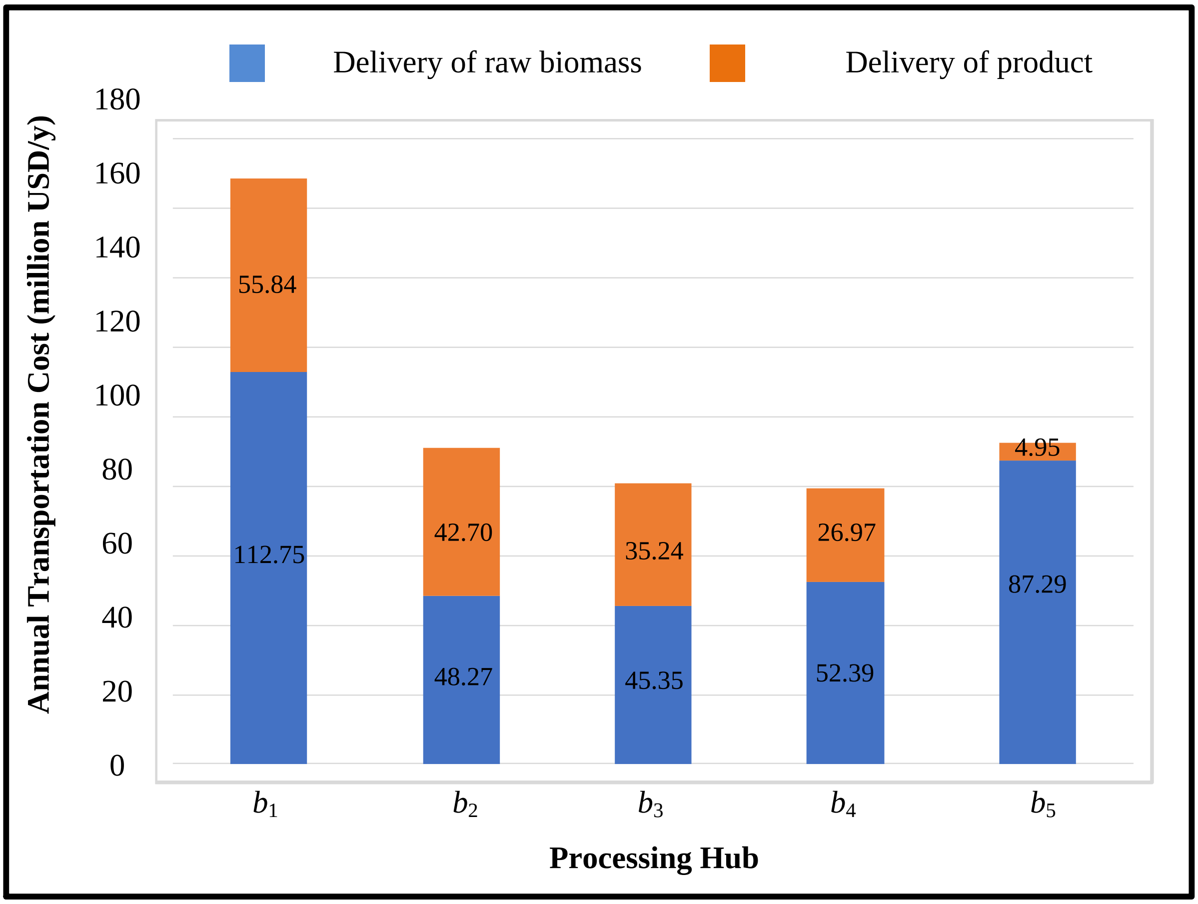

Figure 4-6: AC^{PR} for each location selected as the centralised processing hub

As shown in *Figure 4-7*, EFB is separated into long and short fibres which are further processed into pellet and DLF in the processing hub, whereas PKS is utilised for pellet and energy pack production. Among all the fermentation methods, hot water fermentation is selected to produce bioethanol from sugarcane bagasse. For pineapple biomass, solid and liquid wastes are fermented to produce citric and formic acid respectively. Biochar, syngas and biooil are synthesised via slow pyrolysis of rise husk. Energy produced from the combustion of paddy straw is insufficient to sustain the operation of the plant. Therefore, utility is imported to fill in the energy shortage. Although EFB, PKS and bagasse are also allowed for utility generation in the formulation, the model tends to produce minimum utility. This can be explained by the cheap energy price in Malaysia. Besides, the low utility sale price is low to favour its exportation.

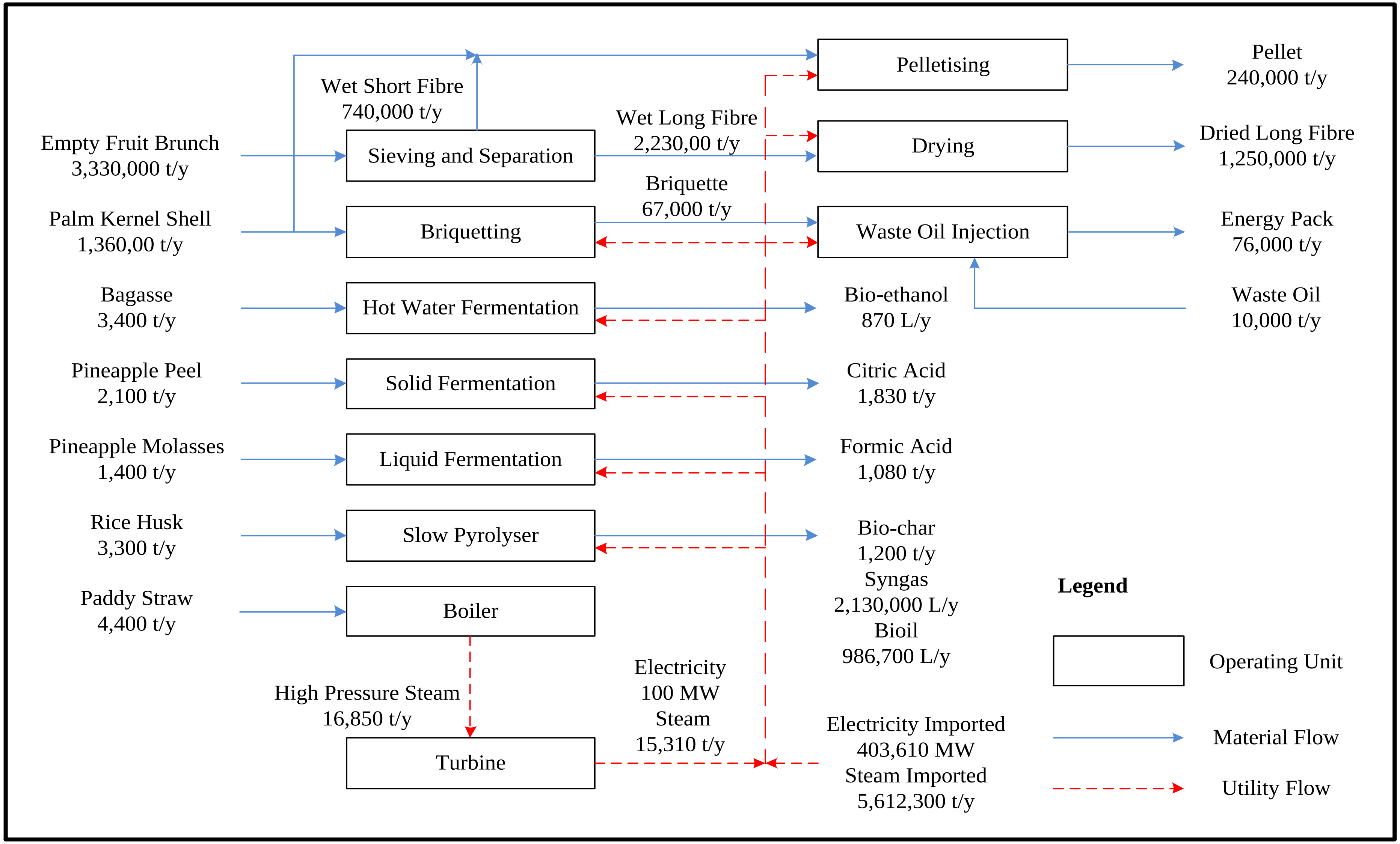

Figure 4-7: Optimum processing hub structure

To verify this situation, the price of steam is adjusted. First, the import steam price is increased. When it reaches 8 USD/kWh, the steam generation increases to fully sustain the processes of the entire plant. This is because the production cost of steam is lower than the buying cost of steam. In the second scenario, the export electricity cost is adjusted from 4 USD/kWh to 8 USD/kWh. At this point, all combustible raw material is fed into the boiler to produce steam due to the higher profit generated from steam as compared to other value-added products. It is also noticed that the optimum location of the centralised processing hub tends to shift from b_4 to b_3. When steam production increases, the synthesis of other value-added products reduces. To determine the transportation cost, the hub-to-port distance becomes less dominant as compared to source-to-hub. Therefore, the shorter source-to-hub distance makes b_3 a better location as compare to b_4. From the results obtained as shown in *Table 4-8*, it can be concluded that the price of the material affects the optimum structure of the hub. In fact, the logistic network and the hub structure is highly correlated.

Table 4-8: Electricity generation

	Price (USD/t)		**Steam Generation**	**Optimum Hub**
	Import Steam	**Export Steam**		
Base Case	6	4	Minimum	b_4
Scenario 1	8	4	Self-sustain	b_3
Scenario 2	6	8	Maximum	b_3

To determine the optimum hub number, the following constraint is incorporated into the model.

$$0 \leq \sum_{b \in B} \beta_b \leq 5 \tag{4.24}$$

The number of hubs is adjusted from 1 to 5 in turn to study the relationship between hub number and gross profit. The results are illustrated in *Figure 4-8*. As observed, the AC^{GP} first increases when the hub number is tuned to 2. When there are more processing hubs available, the chance of biomass sources to be allocated to a nearer processing plant is higher. This leads to a reduction in AC^{TP}, resulting in a better economic potential of the supply chain system. Simultaneously, the AC^{IN} increases with the number of hubs. This explains why the AC^{GP} starts to decline gradually as hub number is continuously being turned down. From 3 hubs onward, the reduction in AC^{TP} plateaus and AC^{IN} turns into a more dominant factor as compare to AC^{TP}. In other words, the reduction in logistic cost can no longer compensate the capital cost of processing hub set up. Therefore, the optimum supply chain configuration of this case study contains 2 processing facilities, which are b_3 and b_4. However, the optimum solution is not necessarily the best for the investor. The decision on the hub number to be setup is always depending on the initial capital available of the investor.

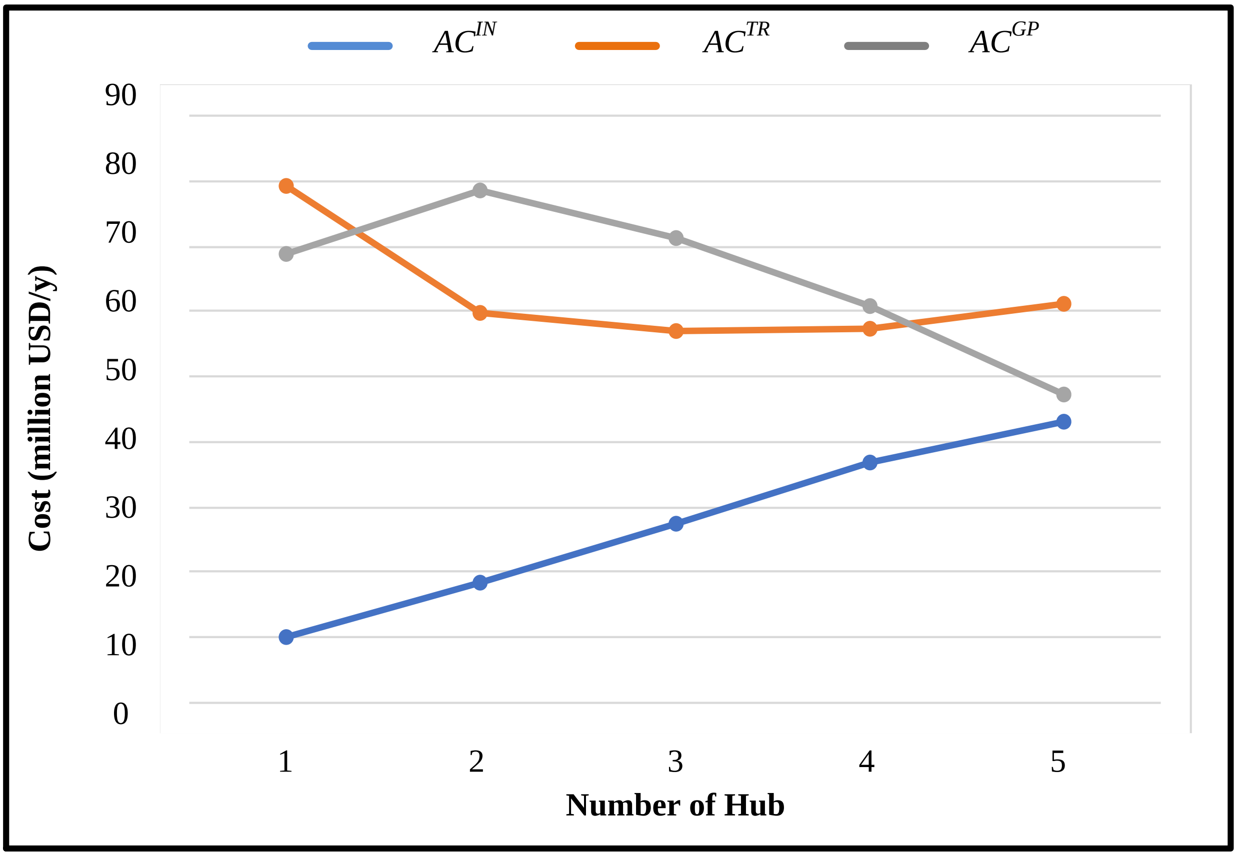

Figure 4-8: The relationship between number of hub and gross profit

4.6 Conclusion

In Chapter 4, multiple biomass corridor (MBC) is proposed for the enhancement of green economic. Based on the concept, a systematic methodology is developed to formulate a mathematical model for the synthesis of an integrated biomass supply chain. The approach is capable of incorporating multiple biomass sources and different processing technologies, generating an optimum supply network, production pathway and delivery network. This framework is successfully illustrated on a case study in Johor, Malaysia. In the base case, 4 types of biomass resources are allocated from 25 locations to a centralised integrated processing hub selected among 5 of the potential locations. The optimum processing structure is determined, and an optimum logistics structure is generated. The base case is extended to analyse the transportation costs of respective hubs being selected as the centralised processing facility. The findings show that the transportation costs of raw material and product are equally important to determine the optimum processing facility. However, the former becomes the more dominant factor as the hub-port distance decreases, or the hub production reduces and vice versa. Another sensitivity analysis is conducted to test the effect of material cost on the supply chain system. The result shows that the processing structure is highly sensitive to the cost of material. It is also noted that processing structure and the logistic network is highly dependent on each other. In the second sensitivity analysis, the gross profit of the supply chain is observed when the hub number is adjusted. Based on the result obtained, supply chain network with 2 centralised processing hubs is optimum. It is concluded that the trade-off between capital cost and transportation is crucial to determine optimum hub number. In this work, the model considers only centralised pre-processing and processing. To ensure the optimality of the entire system, the work is extended to incorporate decentralised pre-processing and processing in the synthesis of an integrated biomass supply chain in Chapter 5.

CHAPTER 5

P-GRAPH-AIDED DECOMPOSITION APPROACH (PADA) FOR THE CENTRALISATION AND DECENTRALISATION OF INTEGRATED BIOMASS SUPPLY CHAIN

5.1 Introduction

In petrochemical industries, process synthesis and design have always concentrated in optimising processes at a single site. As raw materials utilised at a conventional petrochemical plant appear as standardised commodities in the market, they have no or negligible impact on the overall structure of the process. Besides, the configuration of the chemical plant is not critically dependent on the location or the regional setting of the site. Therefore, optimisation of process synthesis and design problem are expected to develop an optimum and cost-efficient integrated structure to convert raw materials to final products regardless of conditions outside of the factory gate.

The case is completely different for the biorefinery industry. Different from raw materials of a petrochemical plant, biomass resources are scattered in a region with specific settings. On top of that, biomass varies in a wide range in terms of quality, shelf life and transport density, which are dominant factors in the determination of logistic and process structure. With these properties, the production of bulk bioproducts is at an economic disadvantage. Instead of concentrating process steps in one central unit, an integrated supply chain must be seen as a production site consisting of a mix of decentralised and centralised processing units depending on the natural and agricultural setting of the region.

Centralised supply chain structure consists of a single and integrated processing facility to produce and distribute products with multiple distribution points. For decentralised processing, the structure consists of multiple facilities that cover different processes, allowing operation close to the source and demand. There is no absolute right or wrong to choose between these supply chain structures as they have their respective pros and cons. Adoption of supply chain structures depends solely on the nature of the process and both centralised and decentralised processing may appear in the same supply chain system. *Figure 5-1* illustrates different types of supply chain structures adopted in biorefinery industry.

For conventional supply chain, centralised processing is always preferred as the unit per unit products cost is relatively lower for having a single processing facility. As biomass have a low transport density by nature, decentralised supply chain configuration has been suggested to improve its economic performance by reducing the logistic cost (Ng and Maravelias, 2017). Moreover, on-site pre-processing or processing guarantees the quality of biomass with short shelf life. However, this is not necessarily favourable for all biomass supply chain system. For instance, forest-based biorefinery supply chains in regions with a highly developed forestry sector, favour centralised production (Pettersson et al., 2018). Contradictorily, the distributed supply chain configuration becomes more competitive with dispersed biomass availability (De Jong et al., 2017). The identification of cost-efficient supply chain configuration is crucial to ensure the commercialisation of large-scale of biorefineries. This work, hence, proposes a systematic approach to determine the optimum configuration of an integrated biomass supply chain, whether centralised or decentralised. To illustrate the proposed approach, the case study in Chapter 4 is revisited.

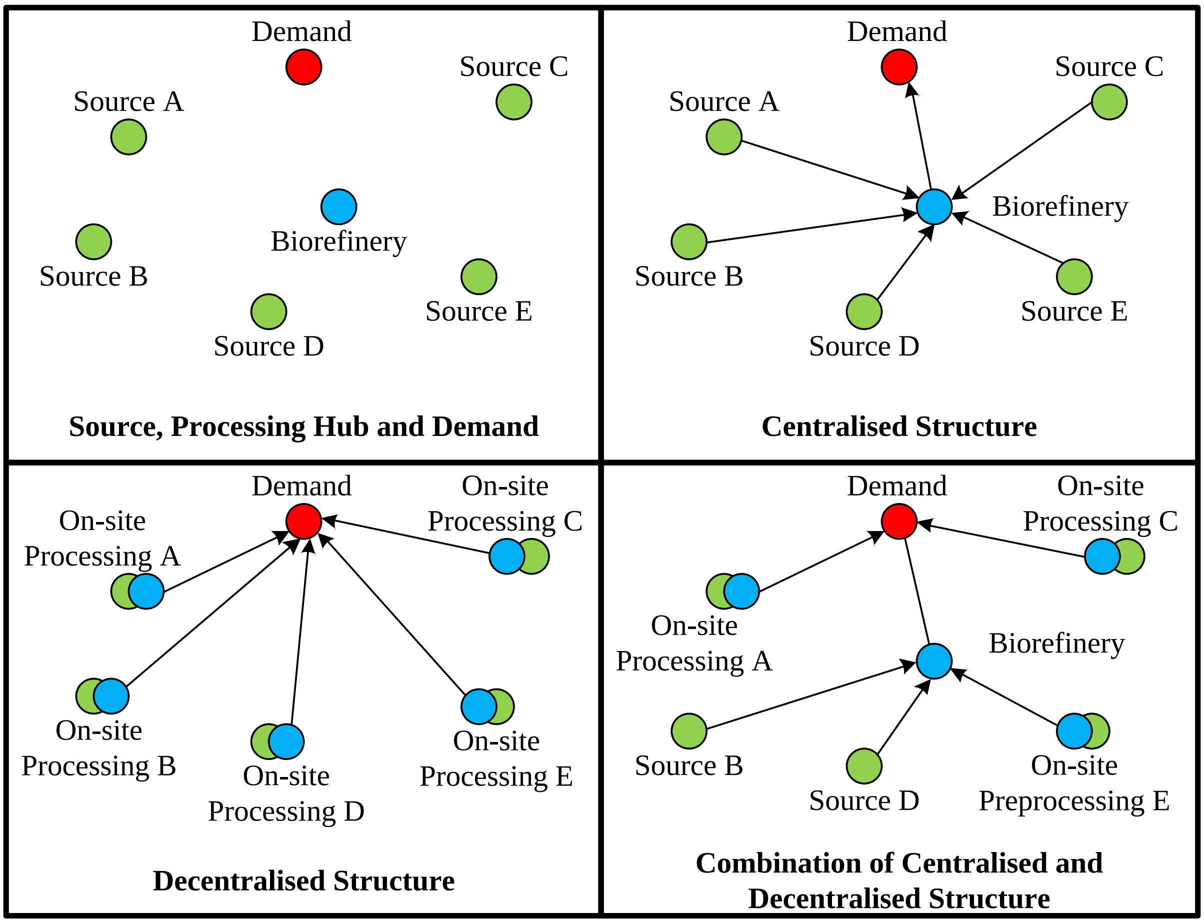

Figure 5-1: Different types of biomass supply chain structure

5.2 Problem Statement

Biomass is locally available by nature, which defines it as a distributed resource, requiring extensive infrastructure networks for transportation and processing. The logistic and infrastructure network are greatly affected by the transport density and shelf life of the biomass. The problem statement of this work therefore can be formally addressed as follows: a set of decentralised biomass sources $a \in A$ is to be pre-processed into precursors onsite at $a \in A$ or centrally at integrated biorefinery $b \in B$. Similarly, these precursors are then further processed into respective products directly at $a \in A$ or in a centralised integrated biorefinery $b \in B$. The products are then finally transported from site $a \in A$ or centralised integrated biorefinery $b \in$

B to demand *c* ∈ *C*. *Figure 5-2* presents the generic superstructure of the problem defined. To determine the optimum structure of an integrated biomass supply chain, a P-graph aided decomposition approach (PADA) is proposed in this work. The following section further explains the methodology developed for this work.

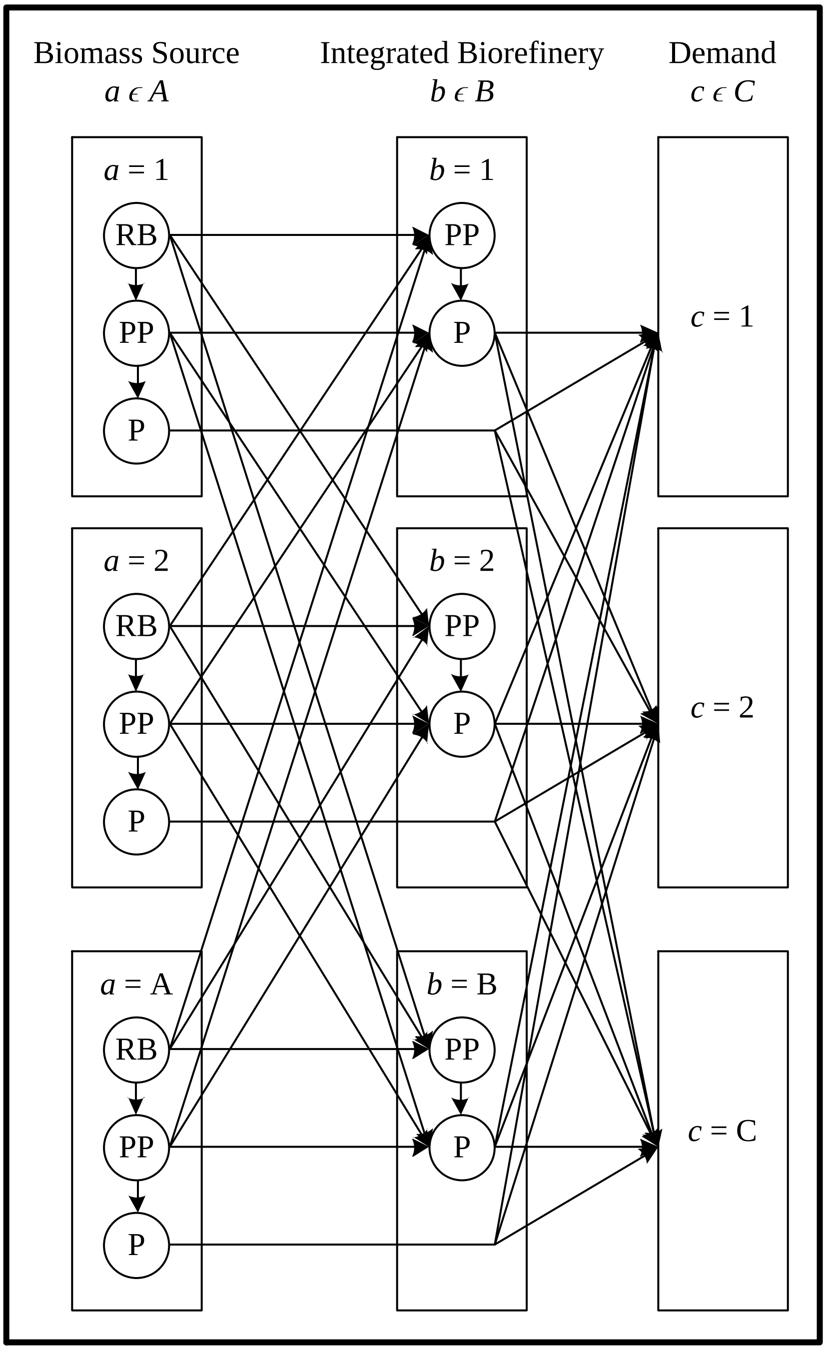

Figure 5-2: Generic representation of this work

5.3 Methodology

Centralisation and decentralisation of processing facilities as an integrated biomass supply chain problem is complex to model. It presents a large number of alternative routes, introducing a layer of combinatorial complexity in addition to the models of the processing and transportation unit operations. To reduce the computational effort, this chapter proposes a P-graph aided decomposition approach (PADA) for the synthesis of integrated biomass supply chain. The conceptual idea of PADA is presented in *Figure 5-3*.

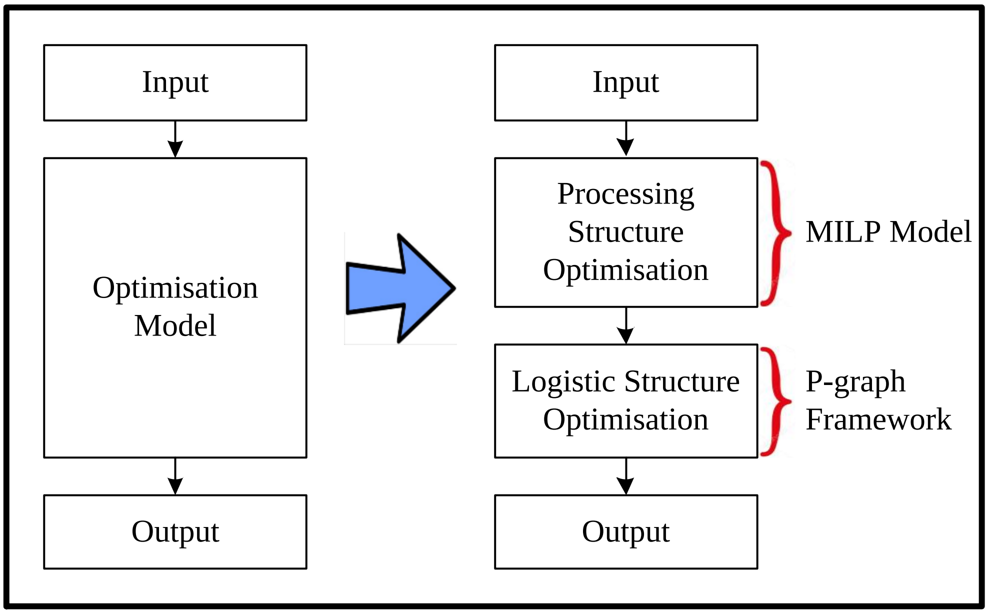

Figure 5-3: Conceptual idea of PADA

The term "decomposition" indicates that the complex integrated biomass supply chain synthesis problem is broken into two simpler sub-problems. Instead of solving the large size problem at once, it is suggested to synthesise and optimise the processing structure first, and then followed by the logistic structure. MILP model developed based on MBC previously in Chapter 4 can be adopted to solve the former stage but not the latter stage. As it represents the selection of the processing structure by integer variables, it makes the centralisation and decentralisation problem becomes very huge. For huge problems, application of this approach becomes increasingly difficult because (Lam, 2013):

i. As the size of the algebraic optimisation problems grows, the solver needs to examine clearly infeasible combinations of integer variable values.
ii. The huge number of different processing structure options makes it rather difficult to build the necessary problem superstructures heuristically and even automatically without rigorous combinatorial tools.
iii. When a superstructure is created heuristically, certain low-cost options would be lost together with opportunities for optimal solutions.

For handling process synthesis problems of practical complexity, the application of P-graph framework is more efficient This is because accelerated branch-and-bound algorithm (ABB) in P-graph allows for a more efficient search of solution topologies as compared to conventional branch-and-bound solvers used for MILP models (Varbanov and Friedler, 2008). Besides, P-graph is more user-friendly towards decision makers from different background due to its visual interface for data encoding and result displayed. Multiple sub-optimal solutions are generated simultaneously for the user to compare with the optimum solution. Therefore, P-graph approach is adapted to solve the logistic structure synthesis in this framework.

Figure 5-4 presents the methodology of PADA for the synthesis of integrated biomass supply chain. As shown in the figure, the step-by-step procedure of optimum technology network synthesis has been explained formerly in Chapter 4. Hence, this chapter focuses only on the development of P-graph framework in PADA. The P-graph utilisation in PADA will be discussed in detailed in the next section.

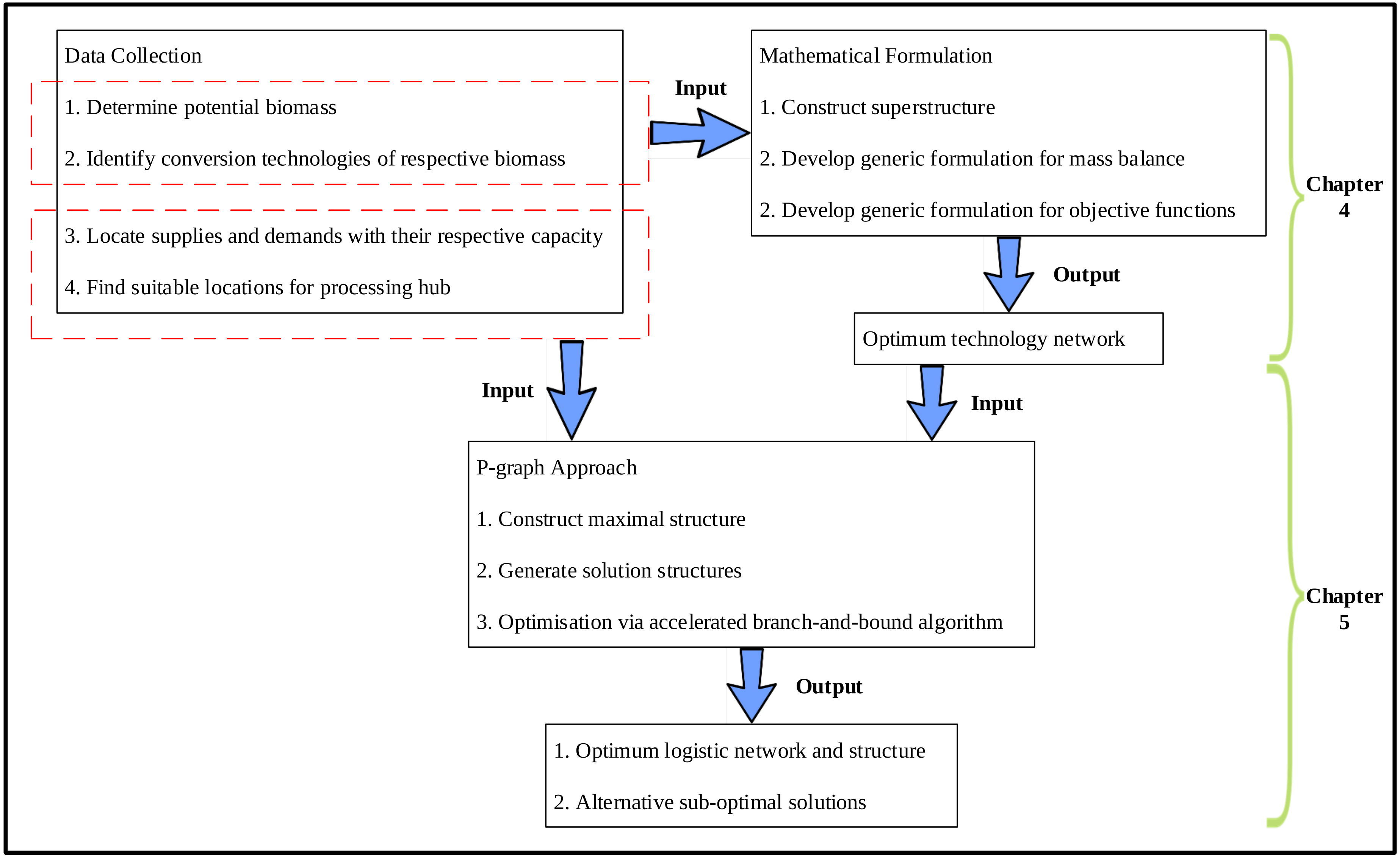

Figure 5-4: PADA for the synthesis of integrated biomass supply chain

5.4 P-graph Framework

Firstly, mathematical model formulated based on MBC is applied to synthesise the technology network as shown in *Figure 5-4*. The objective function is modified as follows:

$$Maximise\ AC_{PH}^{GP} \tag{5.1}$$

$$AC_{PH}^{GP} = AC^{RE} - AC^{PR} \tag{5.2}$$

AC_{PH}^{GP} refers to the annualised gross profit generated from the processing hub. The objective function is then solved, subjecting to Equation 4.7 – 4.14 and 4.18 – 4.19 to determine the optimum structure of the biorefinery.

Next, P-graph framework is adapted to optimise the logistic network of the supply chain. The maximal structure of the logistic network is first constructed using P-graph Studio. Maximal structure is defined as the integration of all combinatorially feasible process structure of a synthesis problem. To represent logistic structure options for supply chain as maximal structure in P-graph, the candidate materials and operating units are identified and linked together with streams. As for candidate materials, their costs and availabilities have to be specified; while for candidate operating units, their conversion ratio, operating cost, capital cost and capacities have to be determined.

Figure 5-5 shows the generic representation of the maximal structure of a logistic network. In the supply chain system, biomass at source *a* is allowed to be: (i) converted to intermediate and product at source *a*, (ii) converted to intermediate and product at centralised hub *b* or (iii) converted to intermediate and product at source *a* and centralised hub *b* alternately. The products produced at source *a* and centralised hub *b* are then sent to demand *c*. *Figure 5-5* is just a simple illustration with single source, single hub and single demand. In fact, the model is capable of capturing multiple sources, hubs and demands.

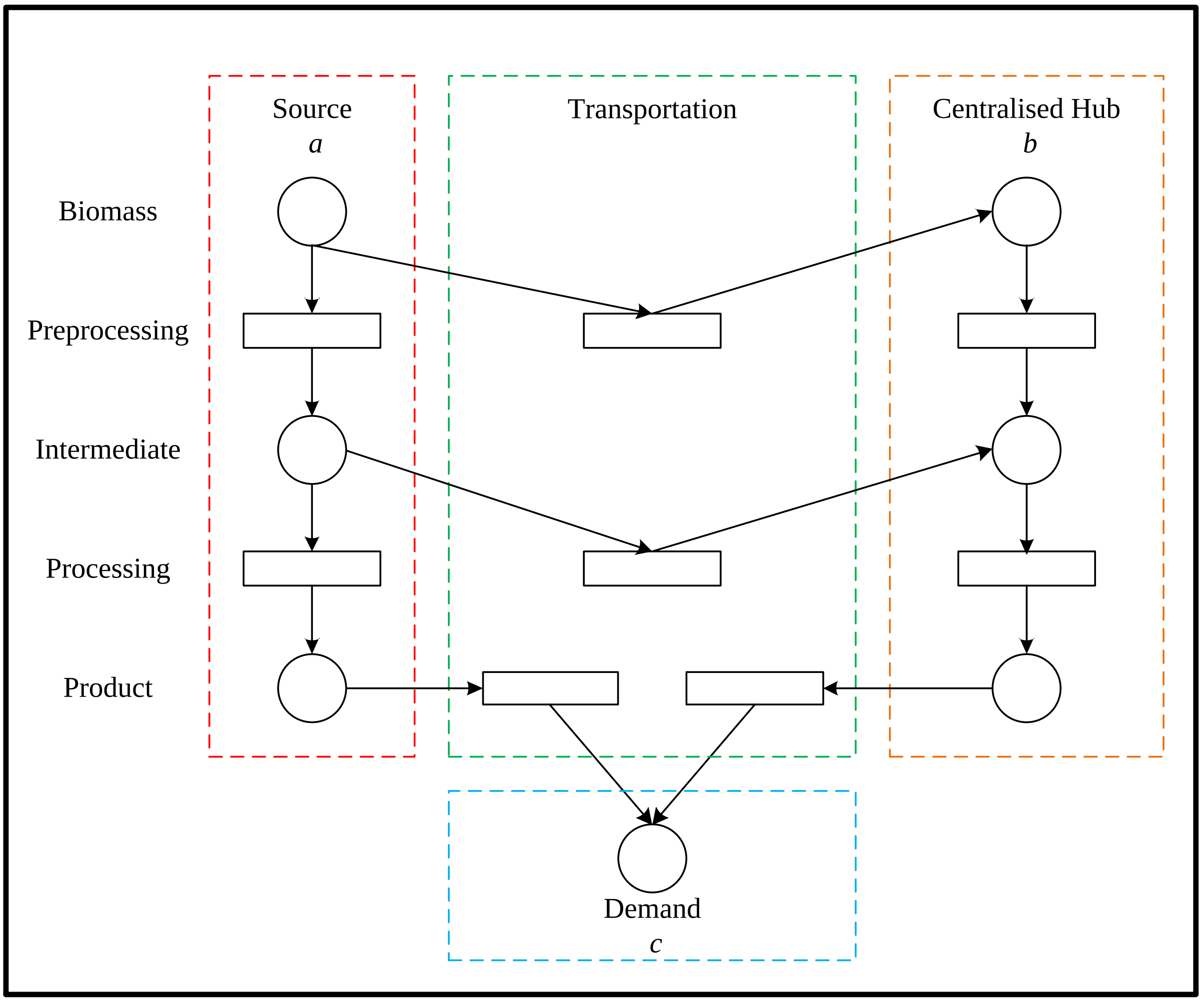

Figure 5-5: Maximal structure of logistic network

In source *a*, the availability of biomass is set as 1 to indicate its existence, ensuring there is a flow in the structure. For the material cost, it is defined as 0. The model denotes the selection of supply chain configuration whether centralised or decentralised as binary variables. Therefore, the capacity of intermediates, products, operating units and transportation in source *a* is bounded by 0 and 1. For time-sensitive biomass, its operation can be decentralised by setting the upper and lower capacity of the processing unit as 1. This constraint is defined to allow onsite processing to prevent the degradation of biomass quality. In centralised hub *b*, the availability and capacity of materials and operating units are bounded by 0 and the number of sources a available. This is to ensure the centralised hub is able to capture the biomass flow from all the sources *a* available. For demand *c*, the capacity of the material is set as the number of sources *a* available to ensure that all biomass sources are fully utilised. Similar to source *a*, its cost is specified as 0. Notice that this stage of the model focuses on the selection of supply chain configuration but not technology selection (which has been done in the first stage). Hence, the conversion ratio of all the operating units is determined to be 1 as no reaction takes place in this model. This also explains why the cost of materials is specified as 0, as cost of material is not a key factor to determine the supply chain configuration.

The dominant factors in this model is transportation cost and capital investment of processing hub. The amount of biomass, intermediate and product at respective source a as well as the distance between source, hub and demand are extracted from the first stage of PADA. The transportation cost $\mathrm{AC_{OU}^{TR}}$ and the capital investment cost $\mathrm{AC_{OU}^{IN}}$ can be calculated via the following equations:

$$\mathrm{AC_{OU}^{TR}} = \mathrm{F^{material}}(\mathrm{FC} \times \mathrm{D} + \mathrm{HC}) \tag{5.3}$$

$$\mathrm{AC_{OU}^{IN}} = \left(\mathrm{C^{Con}} + \mathrm{C^{Land}}\right) \times \frac{\mathrm{RI}(1+\mathrm{RI})^{\mathrm{LS}}}{(1+\mathrm{RI})^{\mathrm{LS}} - 1} \tag{5.4}$$

where $F^{material}$ and D represent the material flow and distance travelled; FC and HC indicate transportation cost and handling cost; $\mathrm{C^{Con}}$ and $\mathrm{C^{Land}}$ is denote cost of construction and land; RI and LS are rate of interest and lifespan of processing facility respectively.

The transportation cost is then input as the operating cost of the transportation operating units in P-graph. As shown in Equation 5.3, the calculation of transportation cost involved the amount of biomass. That is why the amount of biomass is set as 0 previously. For the capital investment, it is inserted as the capital cost of respective pre-processing and processing operating units. As P-graph was first designed intentionally for the synthesis of chemical process routes, materials entering and leaving an operating unit are subject to a conversion ratio. This restriction has to be aware of while constructing the maximal structure.

Scenario 1

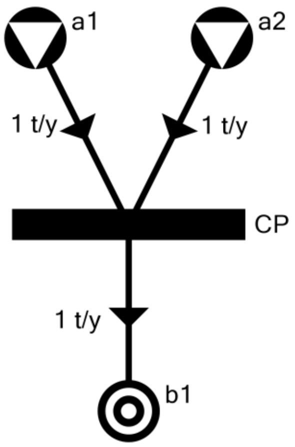

Figure 5-6a: Wrong demonstration

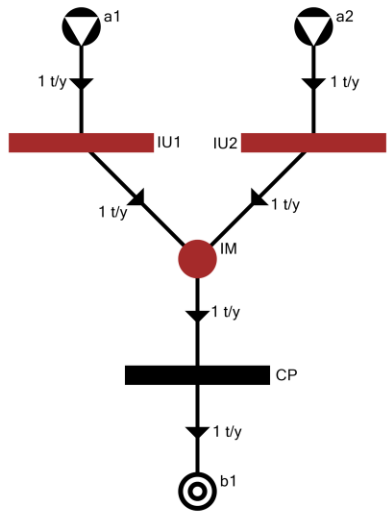

Figure 5-6b: Correct demonstration

Scenario 2

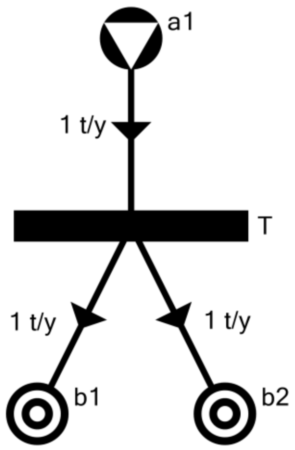

Figure 5-6c: Wrong demonstration

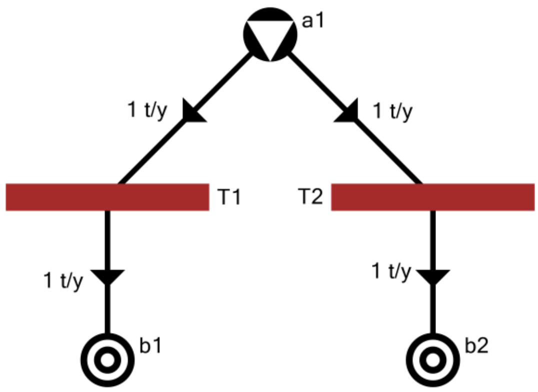

Figure 5-6d: Correct demonstration

Figure 5-6: The wrong and correct demonstration of two scenarios

Figure 5-6 illustrates the wrong and current demonstration of two different scenarios. In the first scenario, two biomass sources with capacity of 1 t/y are to be converted to 2 t/y of product via a centralised processing unit. *Figure 5-6a* displays a mistake which is commonly done in the construction of the maximal structure. In this wrong demonstration, the production is constrained by the input ratio of biomass from both sources. Instead 2 t/y of product, the structure can only synthesise 1 t/y of product. In the second scenario, 1 t/y of biomass is transported to one out of the two hubs. If the maximal structure is created as *Figure 5-6c*, two hubs will receive 1 t/y each from the source due to the output constraint ratio. To eliminate these constrains, imaginary operating units are added, and the correct demonstrations are displayed in Figure *5-6b* and Figure *5-6d*.

With all the data and information input into P-graph, the maximal structure generator (MSG) first determines an overall structure for the problem which encompasses all possible solutions. Next, all the combinatorially individual feasible biomass supply chain solution structures will be identified by solution structure generator (SSG) as subsets of the maximal structure. Lastly, ABB will generate the optimum and near-optimum solutions among the candidate solutions.

With the total annualised transportation cost AC^{TR} and hub investment cost AC^{IN} of the logistic network extracted from P-graph, the optimum gross profit of the supply chain AC^{GP} can be calculated as follows:

$$AC^{GP} = AC^{GP}_{PH} - AC^{TR} - AC^{IN} \qquad (5.2)$$

A case study is then presented in the next section to demonstrate this proposed approach.

5.5 Case Study

To illustrate the proposed methodology, the case study in Chapter 4 is revisited. With the same setting, the biorefinery processing structure is first formulated. As this has been done in Chapter 4, the information is directly imported form the base case modelled. The technology network synthesised in the base case generates AC_{PH}^{GP} of 158 million USD. To apply P-graph framework for the synthesis of supply chain network, the flow of raw biomass, intermediates and products at source *a* are first extracted from the solution report as shown in *Table 5-1*. The output of the model also provides the distance between sources, hubs and demand as tabulated in *Table 5-2*. The transportation cost AC_{OU}^{TR} is then calculated using Equation 5.3. Rate of interest of 10% is assumed for the calculation of investment cost $\mathrm{AC_{OU}^{IN}}$ through Equation 5.4.

Table 5-1: Raw biomass, intermediates and products at each source

Availability (t/y)						
	Raw Material	Product		Raw Material	Product	Intermediate
a_1	1,550	318	a_{14}	200	172	
a_2	10	3	a_{15}	1,174,300	493,750	871,100
a_3	3,550	730	a_{16}	939,400	394,980	696,850
a_4	50	11	a_{17}	352,200	148,090	261,270
a_5	460	95	a_{18}	1,051,400	442,070	779,930
a_6	270	56	a_{19}	469,700	197,490	348,430
a_7	240	50	a_{20}	704,500	296,220	522,600
a_8	100	21	a_{21}	2,770	1,160	
a_9	560	480	a_{22}	2,610	1,090	
a_{10}	670	574	a_{23}	1,600	670	
a_{11}	320	278	a_{24}	380	160	
a_{12}	1,540	1,319	a_{25}	350	150	
a_{13}	170	146				

Table 5-2: Distance between sources, hubs and demand

Point	Distance (km)										
	b_1	b_2	b_3	b_4	b_5		b_1	b_2	b_3	b_4	b_5
a_1	199.0	94.9	112.0	152.0	192.0	a_{14}	170.0	74.7	47.9	38.3	67.6
a_2	21.2	109.0	119.0	133.5	134.1	a_{15}	86.1	23.6	34.2	81.3	121.0
a_3	193.0	89.2	106.0	146.0	186.0	a_{16}	132.0	63.0	44.3	23.4	44.3
a_4	86.1	23.6	34.2	81.3	121.0	a_{17}	90.3	115.0	96.5	43.4	75.6
a_5	129.0	86.1	67.4	30.1	21.8	a_{18}	140.0	32.8	52.5	93.8	134.0
a_6	211.0	95.2	110.0	149.0	189.0	a_{19}	107.0	32.1	22.9	55.1	95.0
a_7	132.0	63.0	44.3	23.4	44.3	a_{20}	135.0	72.1	53.4	19.2	36.5
a_8	90.3	115.0	96.5	43.4	75.6	a_{21}	199.0	94.9	112.0	152.0	192.0
a_9	199.0	94.9	112.0	152.0	192.0	a_{22}	21.2	109.0	119.0	133.5	134.1
a_{10}	193.0	89.2	106.0	146.0	186.0	a_{23}	193.0	89.2	106.0	146.0	186.0
a_{11}	86.1	23.6	34.2	81.3	121.0	a_{24}	86.1	23.6	34.2	81.3	121.0
a_{12}	211.0	95.2	110.0	149.0	189.0	a_{25}	140.0	32.8	52.5	93.8	134.0
a_{13}	90.3	115.0	96.5	43.3	75.6	c	137.9	127.1	101.2	57.9	10.0

In the logistic network, biomass from different sources is allowed to adopt decentralised pre-processing and processing at location of the source itself. Meanwhile, it can be transported to different hubs for centralised pre-processing and processing. Occasionally, it can be pre-processed first before being sent to hub for product synthesis. Therefore, source and demand are identified as the input and output for the construction of maximal structure, while transportation and different processing structures are defined as operating units. Biomass, intermediates and products are produced as intermediates by these operating units. The complete list of materials and operating units in P-graph is presented in *Table 5-2*. As pineapple biomass is prone to microbial spoilage due to the high moisture and sugar content (Lim and Matu, 2015), its operation is modelled as decentralised by assigning 1 as the upper and lower limit of the decentralised processing unit. With all the related data input into the model, the logistic network is synthesised via MSG, SSG and ABB.

Table 5-3: List of materials and operating units in P-graph

Symbol	P-graph Classification	Description
RB_*a*	Input	Raw biomass at source *a*
IN_*a*	Intermediate	Intermediate produced at *a*
PR_*a*	Intermediate	Product produced at *a*
RB_*b*	Intermediate	Raw biomass at source *b*
IN_*b*	Intermediate	Intermediate produced at *b*
PR_*b*	Intermediate	Product produced at *b*
c	Output	Demand
PP_*a*	Operating Unit	Decentralised pre-processing at source *a*
P_*a*	Operating Unit	Decentralised processing at source *a*
PP_*b*	Operating Unit	Centralised pre-processing at hub *b*
P_*b*	Operating Unit	Centralised processing at hub *b*
T_*a*_*b*	Operating Unit	Transportation from source *a* to hub *b*
T_*a*_*c*	Operating Unit	Transportation from source *a* to demand *c*
T_*b*_*c*	Operating Unit	Transportation from hub *b* to demand *c*

The model is first solved by setting b_4 as the only centralised hub. The result obtained is compared with the output of the base case in Chapter 4 to observe how processing structure can affect the overall performance of the supply chain. The optimum supply chain network is then determined by considering all 5 potential hubs in the model. The detailed discussion of the result is presented in the next section.

5.6 Result and Discussion

All the data obtained is input into the software tool P-Graph Studio version 5.2.3.1 and maximal structures of the synthesis problem are generated via the MSG algorithm. *Figure 5-7* to *Figure 5-10* present the maximal structure of sugarcane, pineapple, palm oil and paddy biomass respectively.

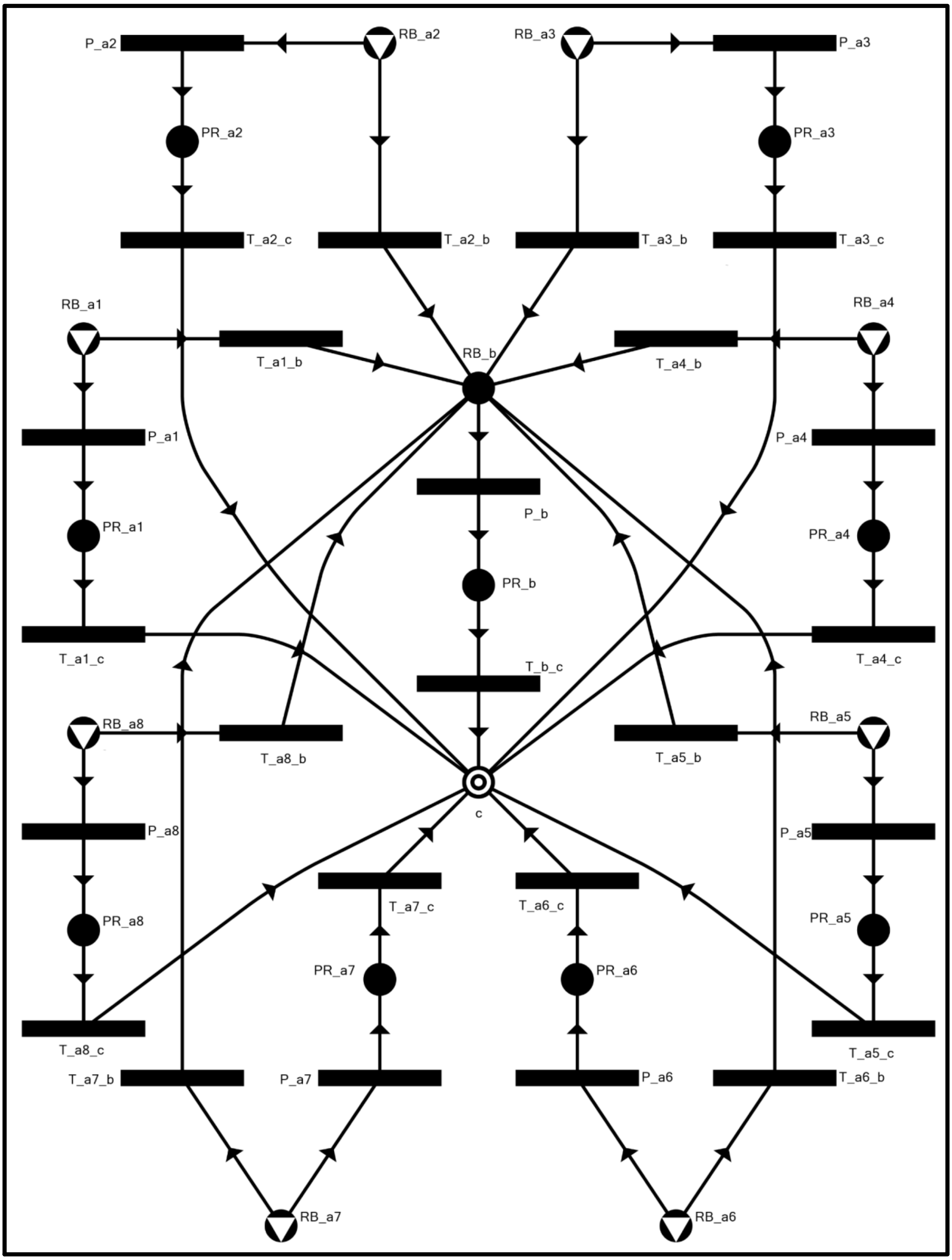

Figure 5-7: Maximal structure of sugarcane biomass supply chain network

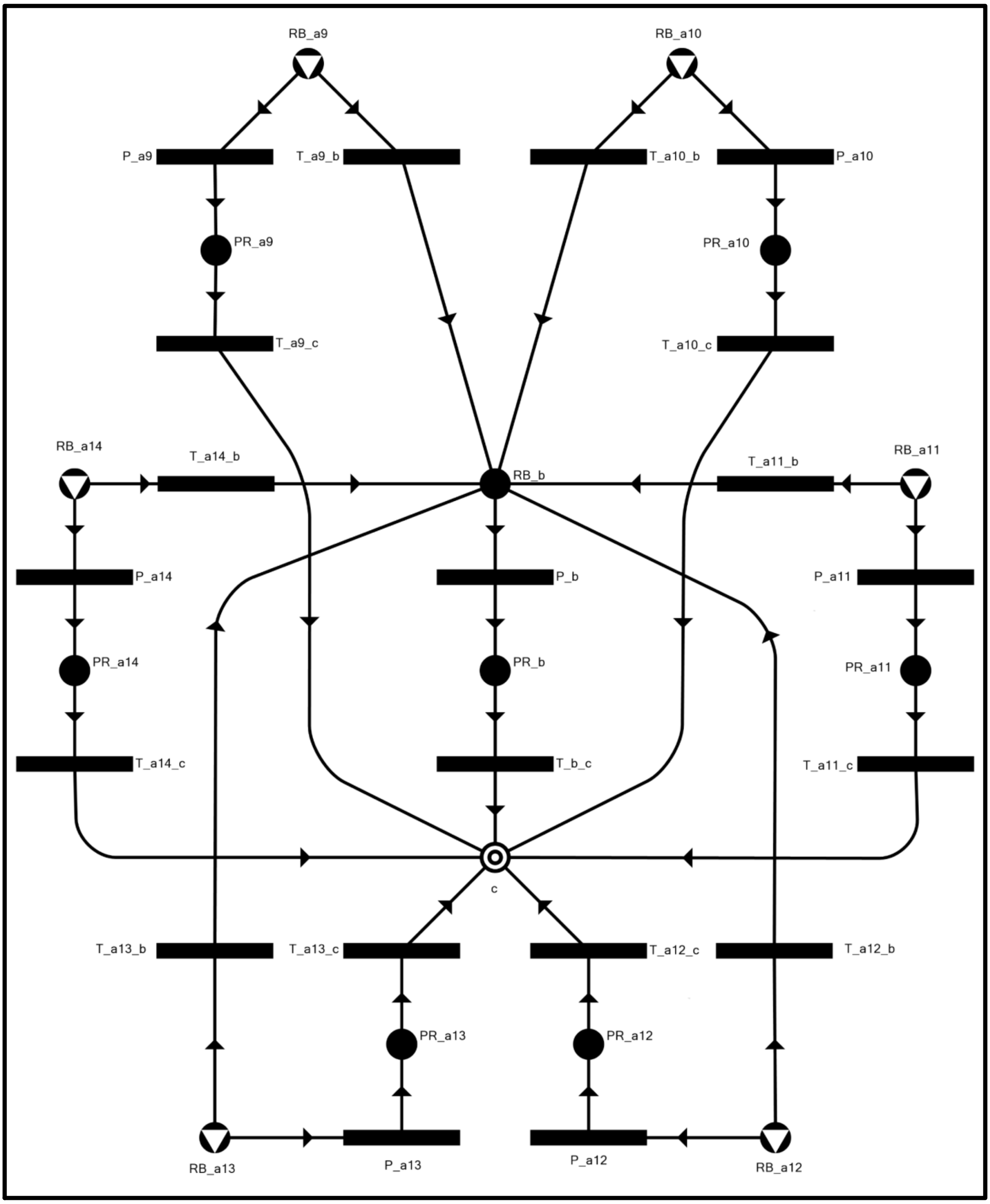

Figure 5-8: Maximal structure of pineapple biomass supply chain network

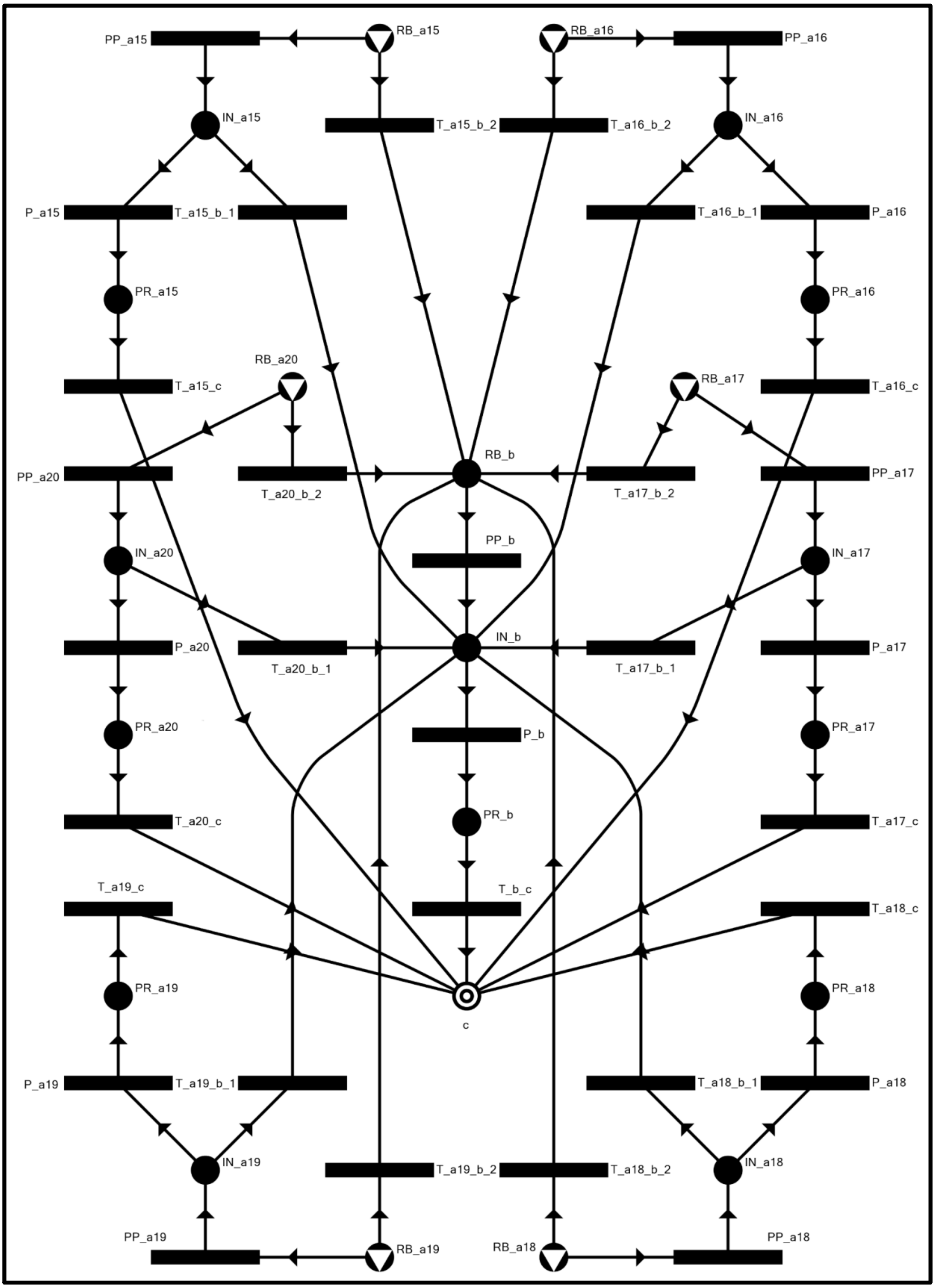

Figure 5-9: Maximal structure of palm oil biomass supply chain network

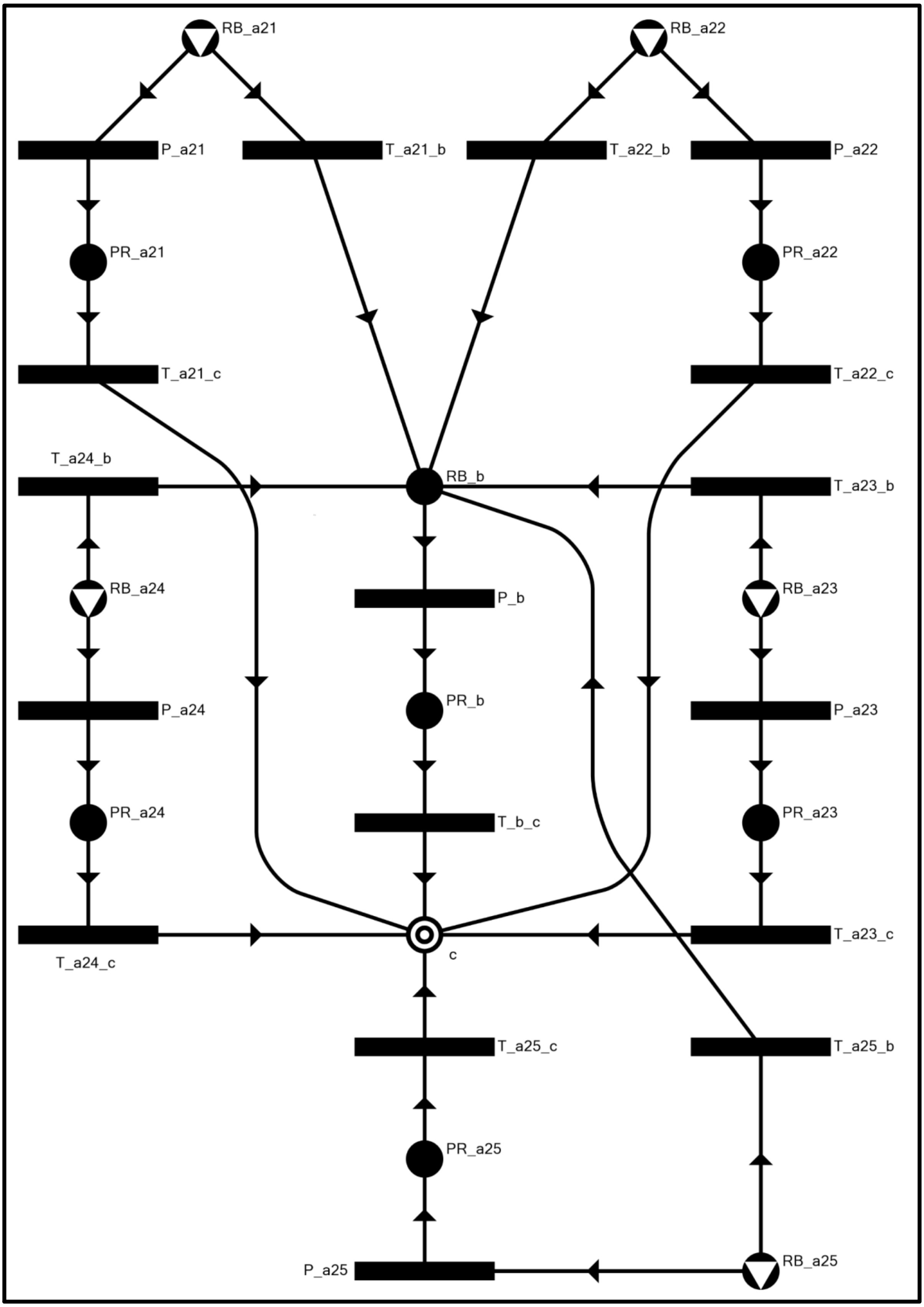

Figure 5-10: Maximal structure of paddy biomass supply chain network

Based on generated maximal structures, 20 optimum and sub-optimum solutions are identified by SSG and ABB. With a computational time of 0.339s, a total of 12,296 subproblems are examined. ABB is very efficient as it is capable to reduce the number and the size of bounding problem, hence reducing the computational effort drastically. The result of the model is compared with the output of the study in Chapter 4. The key findings of both of the model are presented in *Table 5-4*. The AC^{GP} of the resulted structure is 92.04 million USD/y which is about 34.41% of increment overall. This shows that the logistic structure logistic configuration planning in biomass supply chain system is essential to ensure its optimum profitability. As more decentralised hubs are built, the capital investment cost increases by 90.4%. At the same time, biomass with low transport density is allowed to be processed directly at decentralised hubs, resulting in a lower transportation cost. As a result, the increment in AC^{IN} is traded off by the reduction in AC^{TR}, leading to a better AC^{GP}. In this model, the initial capital investment cost is not constrained. However, the initial capital investment of investors is not unlimited realistically. Therefore, the near-optimum solutions now come in place. Investors can select their preferable solution based on their capability to invest.

Table 5-4: Key findings of the model

Parameter	Chapter 4	Chapter 5	% Difference
Annual Transportation Cost, AC^{TR} (million USD/y)	79.36	46.63	-41.24%
Annual Hub Capital Cost, AC^{IN} (million USD/y)	10.00	19.04	+90.40%
Annual Gross Profit, AC^{GP} (million USD/y)	68.85	92.54	+34.41%

The optimised structure is then extracted from P-graph and illustrated in *Figure 5-11*. Due to the fact that pineapple biomass is vulnerable to microbiological contamination, the optimum supply chain network shows that it (a_9, a_{10}, a_{11}, a_{12}, a_{13} and a_{14}) is processed at the location of the source itself to prevent any degradation. Regardless of the distance to hub b4, sugarcane (a_1, a_2, a_3, a_4, a_5, a_6, a_7, and a_8) and paddy (a_{21}, a_{22}, a_{23}, a_{24} and a_{25}) biomass sources are sent for centralised processing. This is because the capacity of these sources is too small, which makes the setup of decentralised processing economically unfeasible.

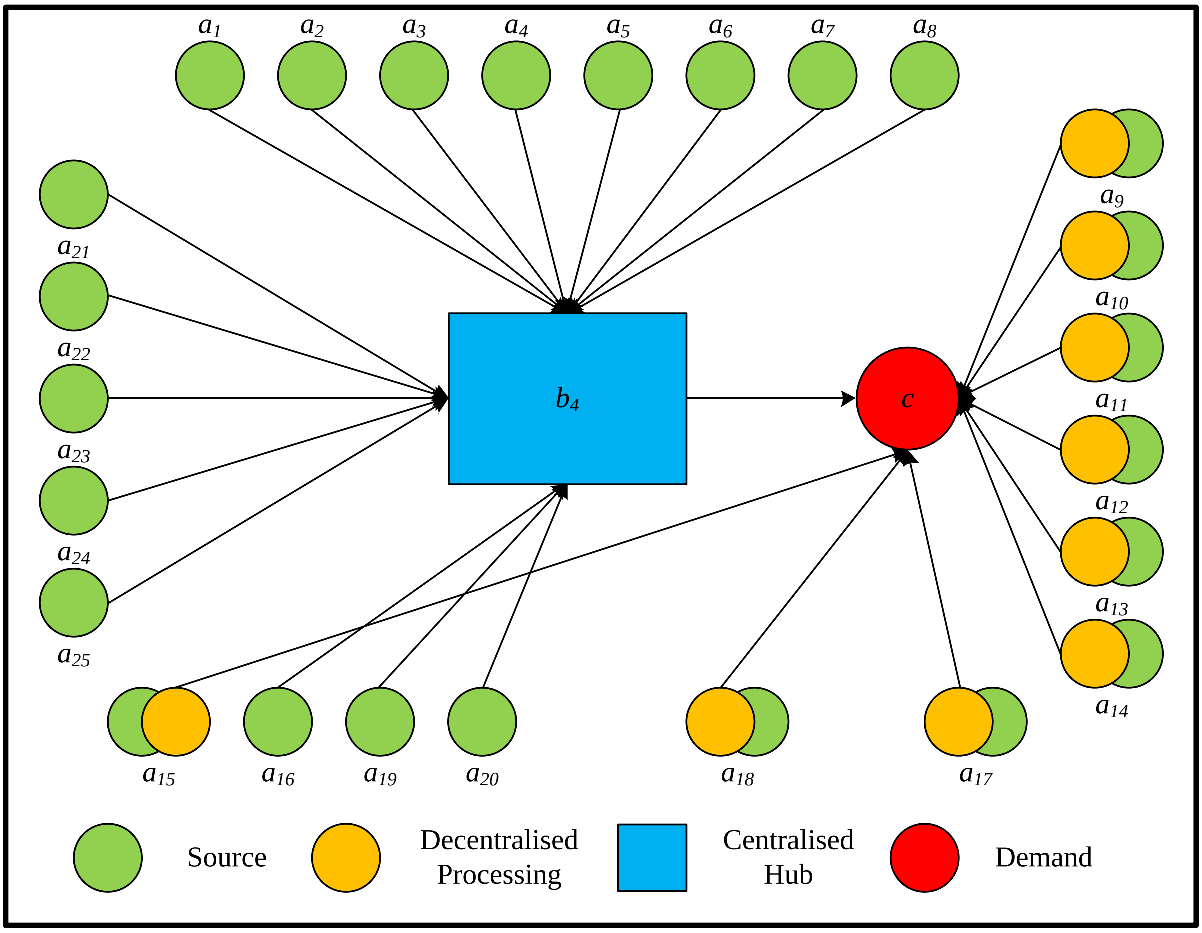

Figure 5-11: Optimised structure for one processing hub

For palm biomass, source a_{16}, a_{19} and a_{20} prefer centralised processing. As they locate near to hub b_4, sharing of processing unit is more economical practical than investing in individual decentralised units. Despite situating close to these sources, a_{15} is processed on-site and sent directly to the demand. The capacity of a_{15} is much higher so transportation of size-reduced product directly to the demand is more cost-effective. The cost saved from transportation is used to compensate the investment in decentralise processing hub. Meanwhile, there are another 2 sources a_{18} and a_{17} which gravitate to decentralised processing. Since they locate near the demand, capital cost for decentralised hub setup is cheaper than cost of transportation to hub b_4.

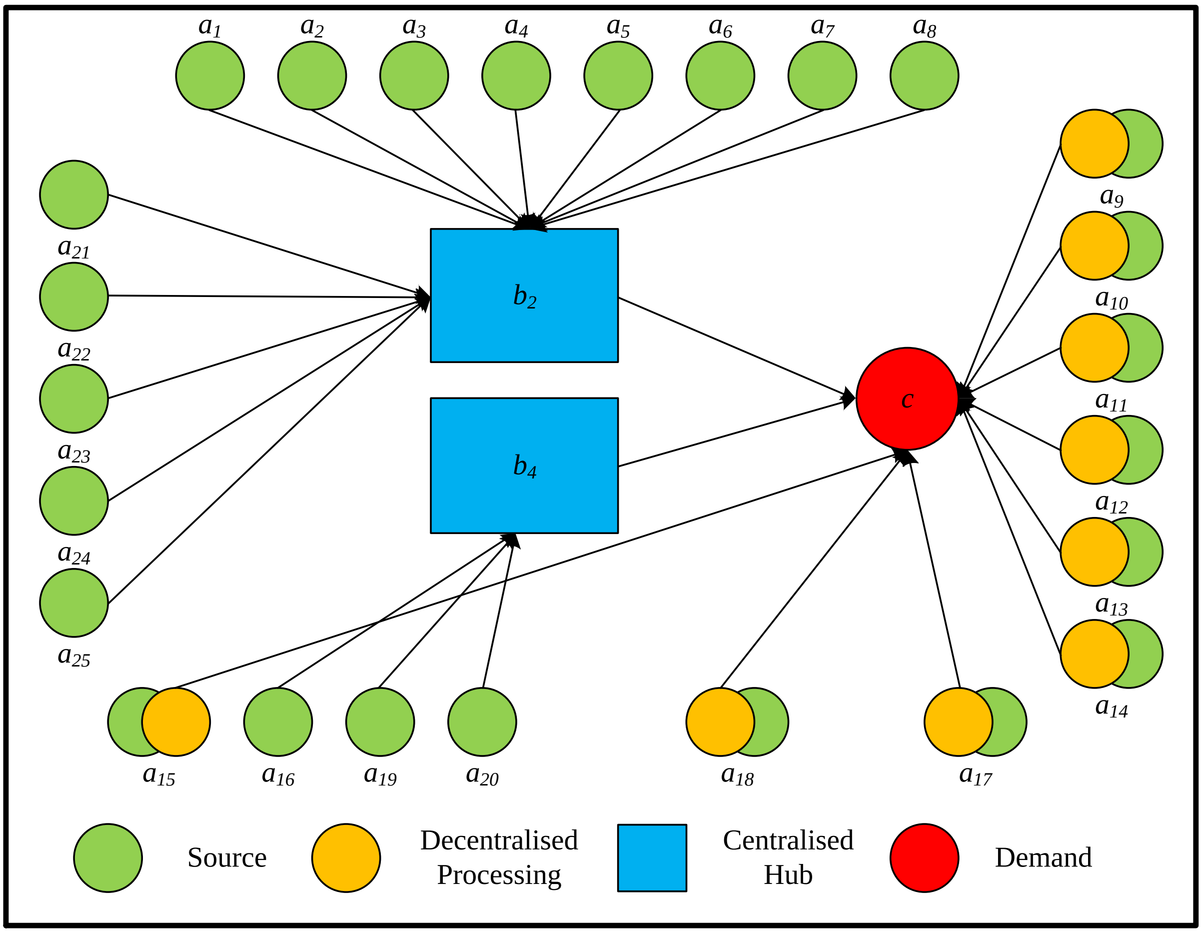

Figure 5-12: Optimised structure for multiple processing hubs

The model is then reconstructed for multiple candidate centralised hubs (b_1, b_2, b_3, b_4 and b_5). The model takes 89.749s to examine a total of 3,390,569 subproblems, which is still very effective. The optimum supply chain structure is extracted and drawn as shown in *Figure 5-12*. It is noted that the location of centralised processing units of sugarcane and paddy biomass has shifted to b_2. As for pineapple and palm biomass, the processing structure remains unchanged. The optimum structure generates a total of 92.61 million USD/y for AC^{GP}. This model identifies a better economic performance for the supply chain. Therefore, it can be concluded that the supply chain configuration has a critical impact on the performance of the overall system.

5.7 Conclusion

In this work, the supply chain configuration, whether centralised or decentralised is discussed. Since there is not a one-size-fits-all solution, P-graph aided decomposition approach (PADA) is proposed to determine the optimum supply chain configuration. This method "decomposes" the complex supply chain synthesis problem into two smaller subproblems. The technology selection is solved via MILP model. As for logistic network synthesis, P-graph framework is adopted as it is capable to solve binaries-intensive problems such as the one addressed in this work. Besides, it has the ability to provide more than one solution at the same time. This unique feature is useful for investors in making decisions, which is successfully illustrated by the case study in Chapter 4. The result shows that there is a drastic increase in the economic performance of the system after considering centralised and decentralised pre-processing/processing structures in the model. This is because the transportation cost outweighs the cost of hub investment. The optimum logistic structure of this case study consists of 2 centralised processing hubs and 9 decentralised processing hubs. In conclusion, supply chain configuration is one of the key impacts that affect the overall performance of the system. It is noted that approaches proposed are focusing on urban region with developed infrastructure. Hence, the synthesis of integrated biomass supply chain in rural area will be discussed in the Chapter 6.

CHAPTER 6

SYNTHESIS OF INTEGRATED BIOMASS SUPPLY CHAIN SYSTEM IN RURAL AND REMOTE REGION VIA RESOURCE INTEGRATED NETWORK (RIN)

6.1 Introduction

In the era of globalisation, rural regions still account for 3.3 billion people or almost half (47.9%) of the world's total population (UN DESA Population Division, 2013). The quality of life in rural regions have always been an issue of concern around the world. This is a heated concern particularly in developing countries because around 70% of the extreme poor in developing countries live in rural regions (IFAD, 2010). Limited infrastructure and transportation facilities, low literacy and low-income result in poor living standards of rural communities.

Usually, agriculture is the fundamental occupation of the rural people and it is the main pillar of rural economy, in which bioresources and food commodities provide foundation for the livelihood of communities. It is no wonder rural regions usually boast an abundance of agricultural crops and biomass. These resources are considered redundant and underutilised due to limitation in transportation, infrastructure, technology and societal understanding. Despite these challenges, the strategy of consuming these rich biomass resources has great potential to create rural non-farm (RNF) job opportunities and boosts the income of the rural society. A good and solid supply chain network will become one of the crucial catalysts in the success of this practise in such a dynamic and potential market. As such, the development of integrated biomass supply chain in remote rural regions is crucial to economic development and the welfare of inhabitants, who are usually among the lowest of low-income groups in the region.

As discussed, previous works often focus on the utilisation of biomass in urban area with well-established transportation facility and infrastructure. To date, there is however no systematic approach for the design and synthesis of integrated biomass supply chain in rural regions. Therefore, this chapter proposes resource integrated network (RIN), a novel approach for the synthesis of integrated biomass supply chain in rural regions, harnessing the underutilised biomass of the region. A Sarawak case study is then solved to illustrate the proposed framework. The model can be a guideline for the development of biomass industry not only in developing countries but worldwide, achieving sustainable development: healthier rural economics, environment and society.

6.2 Resources Integrated Network (RIN)

This section introduces resources integrated network (RIN), a novel approach to synthesise and develop integrated biomass supply chain in rural regions. Rural regions are referred as farms, villages or towns with low population density and small settlements located outside cities. Generally, these regions are closely linked to surrounding agricultural areas. Agriculture being the rural community's primary activity, these areas possess rich bioresources which is a good source of biomass. This is the driving force of the development of the biorefinery industry in rural areas, which can be an alternative sector for the rural community to generate income. However, there are stumbling blocks to the commercialisation of biomass utilisation in rural areas.

Figure 6-1 shows a typical rural community. As shown in the figure, rural regions have limited and poor land transport infrastructure which makes large scale biomass transportation challenging and economically infeasible. As a result, inland waterway transport system that consists of transport by rivers, canals and lakes plays a significant role as an alternative transportation and accessibility of remote and rural areas. Rivers are the lifeblood of the rural community and the healthy flow of rivers is a sign of life in the community. Besides, water transportation is also a relatively more economical mode of transport for bioresources and biomass. The cost of maintaining and constructing routes is very low as most of them are naturally made. The fertility of riverbanks at these inland waterways also greatly contributes to local agricultural activities. Alas, the use of inland waterways in biomass industry has yet to reach its full potential.

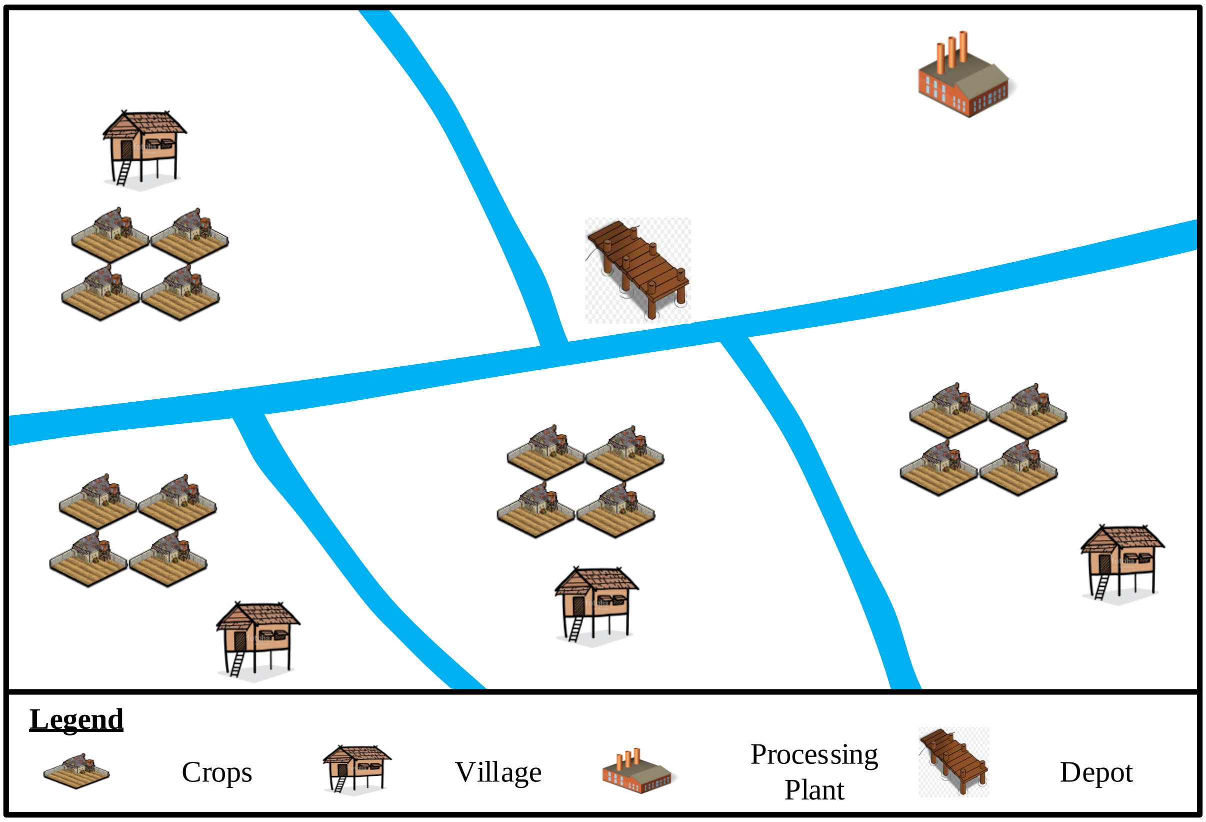

Figure 6-1: A typical rural community

Another challenge arises while developing an integrated biomass supply chain in rural areas is the small production capacity of bioresources and biomass. The size and the population density of the rural community are small which results in a smaller production of bioresources and biomass. Besides, these resources are scattered across rural regions. Hence, creating solely a biomass supply chain in rural region is economically unsustainable. It is suggested to integrate bioresources and food commodities produced by rural communities as well as their daily needs into the supply chain to increase overall economic performance.

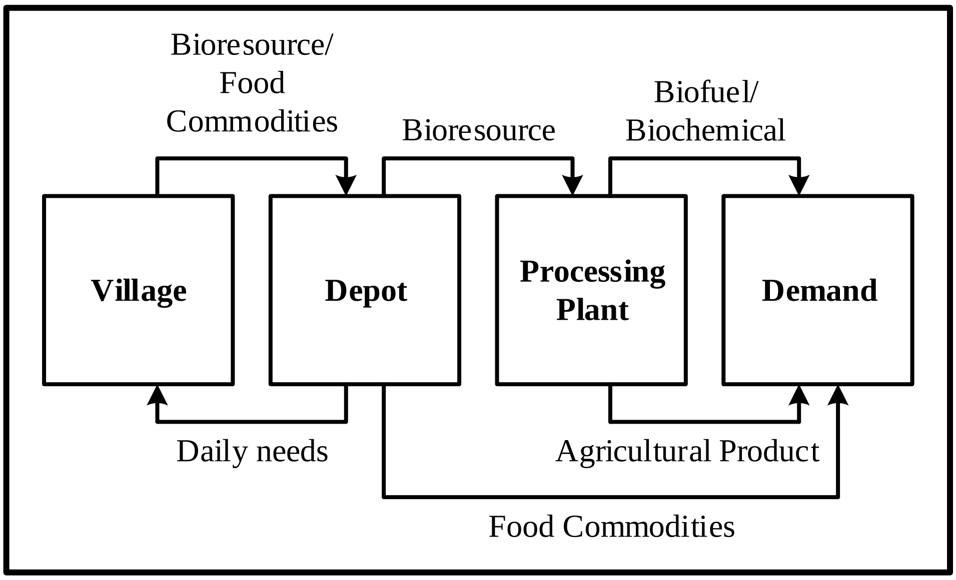

Figure 6-2: The concept of resource integrated network (RIN)

The resource integrated network (RIN), therefore, integrates multiple resources (bioresources, food commodities, biomass and community’s daily needs) into a supply chain system, incorporating inland water transport as an alternative mode of logistic. The concept of RIN is shown in *Figure 6-2*. The community’s daily needs are first transported to the rural villages from the depot. Simultaneously, the bioresources and food commodities produced from the villages are carried and transported back to the depot. From the depot, bioresources are sent for processing, forming various agricultural products. During processing, the biomass generated will be further transformed into biofuel and biochemical. The final products (agricultural products, food commodities, biofuel and biochemical) are delivered to the respective demands. *Figure 6-3* displays an illustrative example of RIN. The detailed RIN framework will be discussed in the next section.

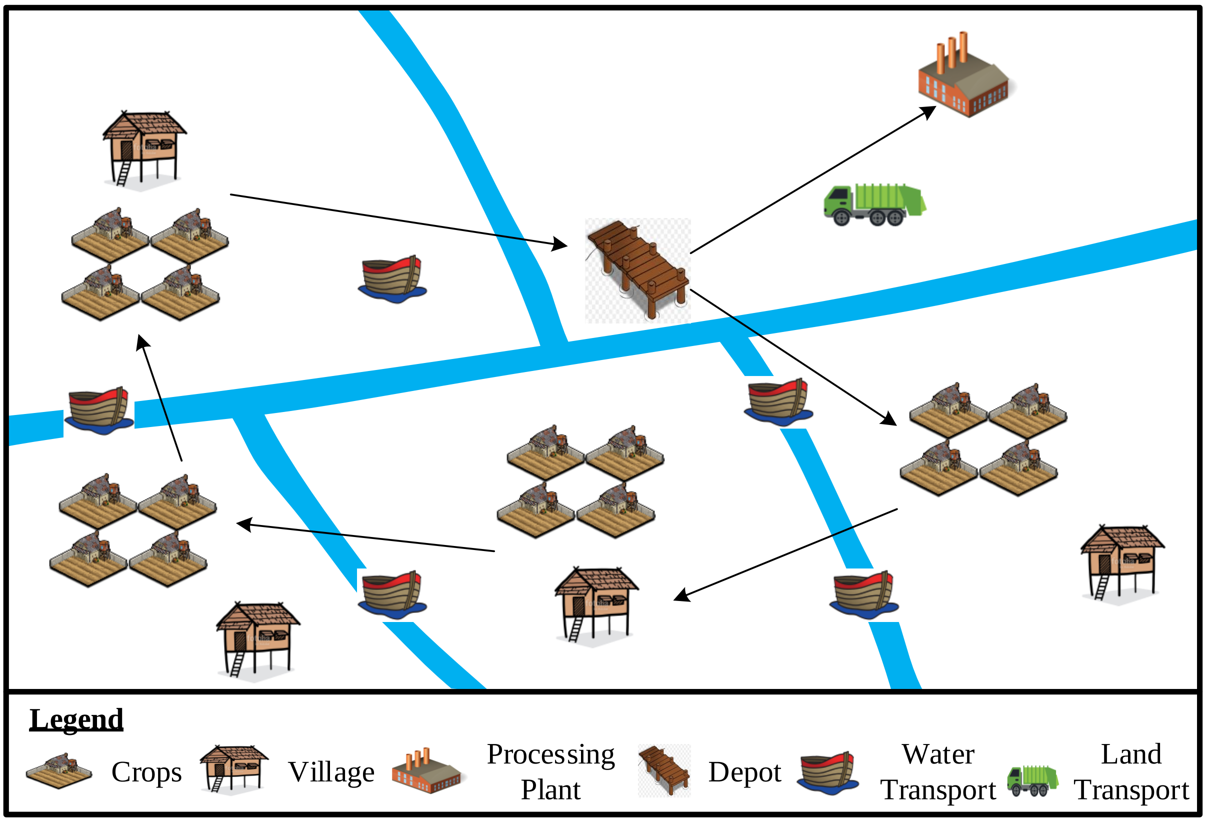

Figure 6-3: Illustration of RIN

6.3 Methodology

Based on the RIN concept introduced, a comprehensive methodology is developed to address integrated biomass supply chain synthesis problem in rural regions as shown in *Figure 6-4*. In this framework, logistic network and technology network are solved in parallel separation. First, the MBC approach in Chapter 4 is adapted and extended to solve the technology network of the supply chain system. A list of potential bioresources and commodities are identified. The processing technologies of these bioresources and potential biomass produced are then determined. With the conversion technologies of the biomass discovered, the data is fed into the model to select the optimum processing technologies. As for the logistic network, the depot and the list of rural villages with their availability and demand capacity is first figured out. The information is then inputted into vehicle routing problem (VRP) mathematical programming to find the optimum logistic network. The detailed extended MBC and VRP mathematical formulation will be shown in detailed in Section 6.3.1 and 6.3.2.

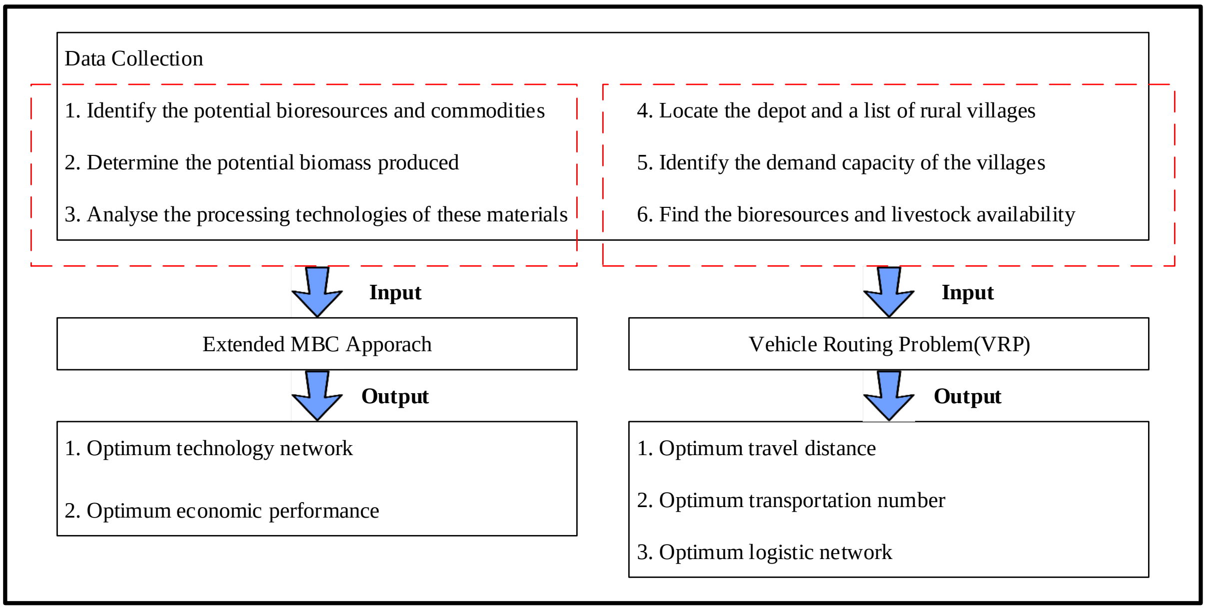

Figure 6-4: RIN methodology

6.3.1 Extended MBC Approach

The MBC model formulated in Chapter 4 is revised to integrate bioresource type and bioresource processing technology into the model. The problem definition for extended MBC is formally stated as follows: given a set of bioresource types $g \in G$ are converted into biomass type $i \in I$ via technology $h \in H$. The resultant biomass is then processed into intermediates $k \in K$ and product $m \in M$ via technologies $j \in J$ and $l \in L$ respectively. The generic superstructure of extended MBC is shown in *Figure 6-5*.

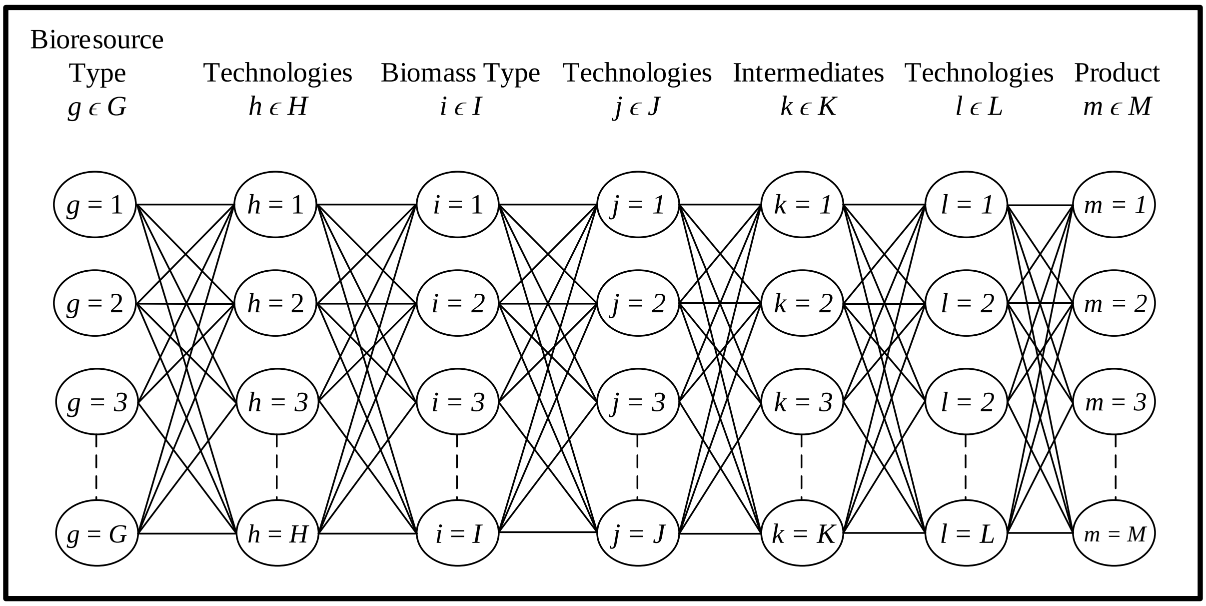

Figure 6-5: Generic superstructure of extended MBC

In the processing unit, $F_{g,h}$ amount of bioresource type g is first converted into F_i amount of biomass type i via technology h with conversion ratio of $F_{g,h}$. The amount of bioresource feed F_g is constrained by the availability of bioresource type g from the depot $\mathrm{CA}_{g,\mathrm{depot}}$.

$$F_g = \sum_{h \in H} F_{g,h} \qquad \forall g \in G \qquad (6.1)$$

$$F_i = \sum_{h \in H} \sum_{g \in G} F_{g,h} \mathrm{CR}_{h,i} \qquad \forall i \in I \qquad (6.2)$$

$$\mathrm{CA}_{g,\mathrm{depot}} \geq F_g \qquad \forall g \in G \qquad (6.3)$$

The biomass type i produced is then transferred to technology j to be processed into intermediate k.

$$F_i = \sum_{j \in J} F_{i,j} \qquad \forall i \in I \qquad (6.4)$$

$$F_k = \sum_{j \in J} \sum_{i \in I} F_{i,j} \mathrm{CR}_{j,k} \qquad \forall k \in K \qquad (6.5)$$

where $F_{i,j}$ is the amount of biomass *i* sent to technology *j*; F_k is the amount of intermediate *k*; $\mathrm{CR}_{j,k}$ is the conversion rate of technology *j* converting biomass *i* to intermediate *k*.

The intermediate *k* is then further processed and converted into final product m via technology *l*.

$$F_k = \sum_{l \in L} F_{k,l} \qquad \forall k \in K \qquad (6.6)$$

$$F_m = \sum_{m \in M} \sum_{k \in K} F_{k,l} \mathrm{CR}_{l,m} \qquad \forall m \in M \qquad (6.7)$$

where $F_{k,l}$ denotes the amount of intermediate *k* sent to technology *l*; F_m is the amount of product m; $\mathrm{CR}_{l,m}$ is the conversion rate of technology *l* from intermediate *k* to product *m*.

The economic performance of the technology network is evaluated by the annualised gross profit of the processing unit AC_{PH}^{GP}. It is the difference between revenue and the cost of production of respective products as shown as follows:

$$AC_{PH}^{GP} = \sum_{m \in M} F_m \mathrm{SC}_m - \sum_{i \in I} \sum_{h \in H} F_i \mathrm{PC}_h - \sum_{k \in K} \sum_{j \in J} F_k \mathrm{PC}_j - \sum_{m \in M} \sum_{l \in L} F_m \mathrm{PC}_l \qquad (6.8)$$

where SC and PC represent the revenue and production cost of respective products.

The optimum technology network selection can be determined by maximising the annual gross profit of the processing unit AC_{PH}^{GP}. Hence, the objective function of extended MBC can be defined as follows:

$$Maximise\ AC_{PH}^{GP} \tag{6.9}$$

In the next section, the formulation of vehicle routing problem (VRP) to calculate the optimum logistic network is discussed.

6.3.2 Vehicle Routing Problem (VRP)

The vehicle routing problem (VRP) is a combinatorial optimisation and integer programming problem. It is formulated to calculate the optimal set of routes for a fleet of vehicles to travel from a central depot in order to visit to a given set of locations. *Figure 6-5* shows an illustrative example of VRP. In this example, optimum routes and number of boat are identified as shown.

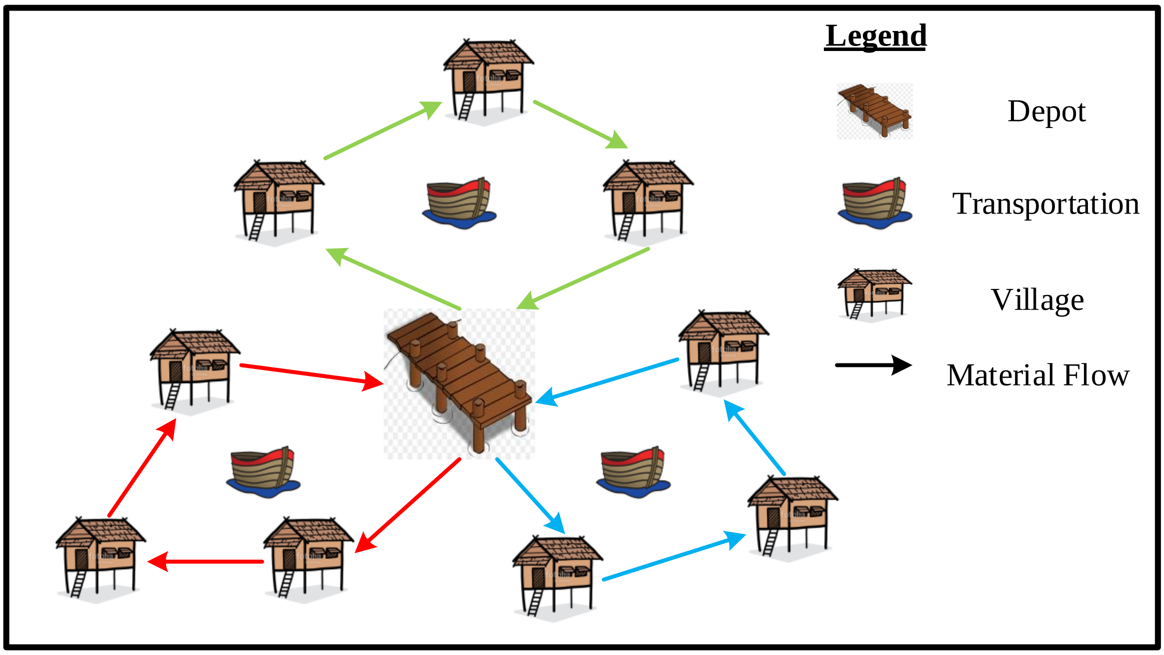

Figure 6-6: Illustrative example of VRP

In RIN approach, VRP is adopted to determine the cheapest route (i.e. shortest) to collect bioresources and food commodities from rural villages via water transport. The problem statement of VRP in RIN can then be formally stated as follows: given a set of villages p ($p = 2,3 \cdots P$) with bioresources and food commodities availability Q_p is to be visited by n number of boats. Each village must be visited by exactly one boat and the sum of availabilities of villages U_p assigned to boat must be less than the boat capacity CA_{boat}. All boats begin and end their route at a centralised depot p_1. The objective is to minimise the sum of travel distance by n number of boats (i.e. cost).

Firstly, the total distanced travelled is calculated via the following equations:

$$D_{total} = \sum_{p \in P} \sum_{q \in Q} D_{p,q}\, x_{p,q} \tag{6.10}$$

$$x_{p,q} \in \{0, 1\} \qquad \forall p \in P, \forall q \in Q \tag{6.11}$$

where $D_{p,q}$ specifies the distance between village p and q ($D_{p,q} = D_{q,p}$) ; $x_{p,q}$ is a binary variable ($x_{p,q} = 1$ means that the boat travels from village p to q, otherwise 0).

Equations 6.12 and 6.13 make sure that each village is visited by one and only once boat. In other words, it means a boat can only enter and exit village r once. Besides, village r cannot travel back to itself. This is constrained by Equation 6.14.

$$\sum_{p \in P\ p \neq r} x_{p,r} = 1 \qquad \forall r \in R \tag{6.12}$$

$$\sum_{q \in Q\ q \neq r} x_{r,q} = 1 \qquad \forall r \in R \tag{6.13}$$

$$x_{r,r} = 0 \qquad \forall r \in R \tag{6.14}$$

The cumulative amount of bioresources loaded from r villages is limited by boat capacity. The following equations guarantee together that the vehicle capacity is not exceeded.

$$\mathrm{CA}_r \leq U_r \leq \mathrm{CA}_{\mathrm{boat}} \qquad \forall r \in R \tag{6.15}$$

$$U_r \geq U_p + \mathrm{CA}_r x_{p,q} - \mathrm{CA}_{\mathrm{boat}}\left(1 - x_{p,q}\right) \qquad \forall p \in P, \forall q \in Q, \forall r \in R \tag{6.16}$$

where CA_r is the availability of bioresources at village r; U_r is the cumulative load at village r; $\mathrm{CA}_{\mathrm{boat}}$ is the capacity of the boat. Equation 6.15 also avoids subtours in the solution, i.e. travelling routes that do not go through the depot.

The total annualised transportation cost of the supply chain network AC^{TR} can be calculated as follows:

$$AC^{TR} = \mathrm{N}_{\mathrm{boat}}\mathrm{AC}_{\mathrm{boat}}^{\mathrm{CC}} + \mathrm{N}_{\mathrm{trip}} D_{total} \mathrm{FC}_{\mathrm{boat}} \tag{6.17}$$

$$\mathrm{N}_{\mathrm{boat}} = \left\lceil \frac{\sum_{p \in P} \mathrm{CA}_p}{\mathrm{CA}_{\mathrm{boat}}} \right\rceil \tag{6.18}$$

where $\mathrm{N}_{\mathrm{boat}}$ and $\mathrm{N}_{\mathrm{trip}}$ is the number of boats and trips; $\mathrm{AC}_{\mathrm{boat}}^{\mathrm{CC}}$ and $\mathrm{FC}_{\mathrm{boat}}$ represent the annualised capital cost and fuel consumption cost per km of the boat. As the number of boats required is an integer, the ceiling of n is taken.

To obtain the optimum AC^{TR}, the total distance travelled D_{total} is minimised. Hence, the objective function can be defined as follows:

$$Minimise\ D_{total} \tag{6.19}$$

6.3.3 Optimum Supply Chain Network

The annualised gross profit of the supply chain network AC^{GP} can then be determined via the following equation.

$$AC^{GP} = AC_{PH}^{GP} - AC^{TR} \tag{6.20}$$

A case study is then presented in the next section to demonstrate the proposed RIN.

6.4 Case Study

The Malaysian state of Sarawak is the home to one of Asia's most biologically diverse tropical rainforests. Due to its geographical location by nature, the tropical state is blessed with an abundance of bioresources and biomass. Sarawak is therefore considered as a hidden gem in the island of Borneo. In the state, rural households have been relying on these agricultural resources as a main source of income. In this respect, this section presents the application of RIN in developing an integrated biomass-cum-bioresources supply chain to diversify the source of income and enhance rural economic opportunities. This case study is conducted in one of the least developed areas around Gigis River in Mukah District, Sarawak. In this work, 7 villages which mainly produce sago logs, fresh fruit brunches, paddies, eggs and catfishes are considered. For the processing hub, bioresources and biomass conversion technologies are first identified for the construction of superstructure as illustrated in *Figure 6-7*.

As shown in the figure, sago starch, sago fibre and sago bark are first produced from sago logs. Sago fibre and sago bark then undergo dilute acid, dilute alkaline hot water or steam explosion pre-treatment to increase ethanol yield prior to fermentation. They can also be utilised to make syngas and biooil through gasification and pyrolysis respectively. From the production of rice, rice husk and paddy straw are generated as waste. Rice husk contains high energy which can be converted into biooil via pyrolysis, whereas paddy straw can be burnt directly to generate energy. As for FFB, it is transformed into crude palm oil (CPO), EFB and PKS. Through sieving and separation, long and short fibre are sorted out from EFB. Next, long fibre can be dried to DLF which is a good source of bioenergy. At the same time, short fibre and PKS can be pelleted and briquetted as solid biofuel. With the injection of motor oil, briquette can be further converted into energy pack.

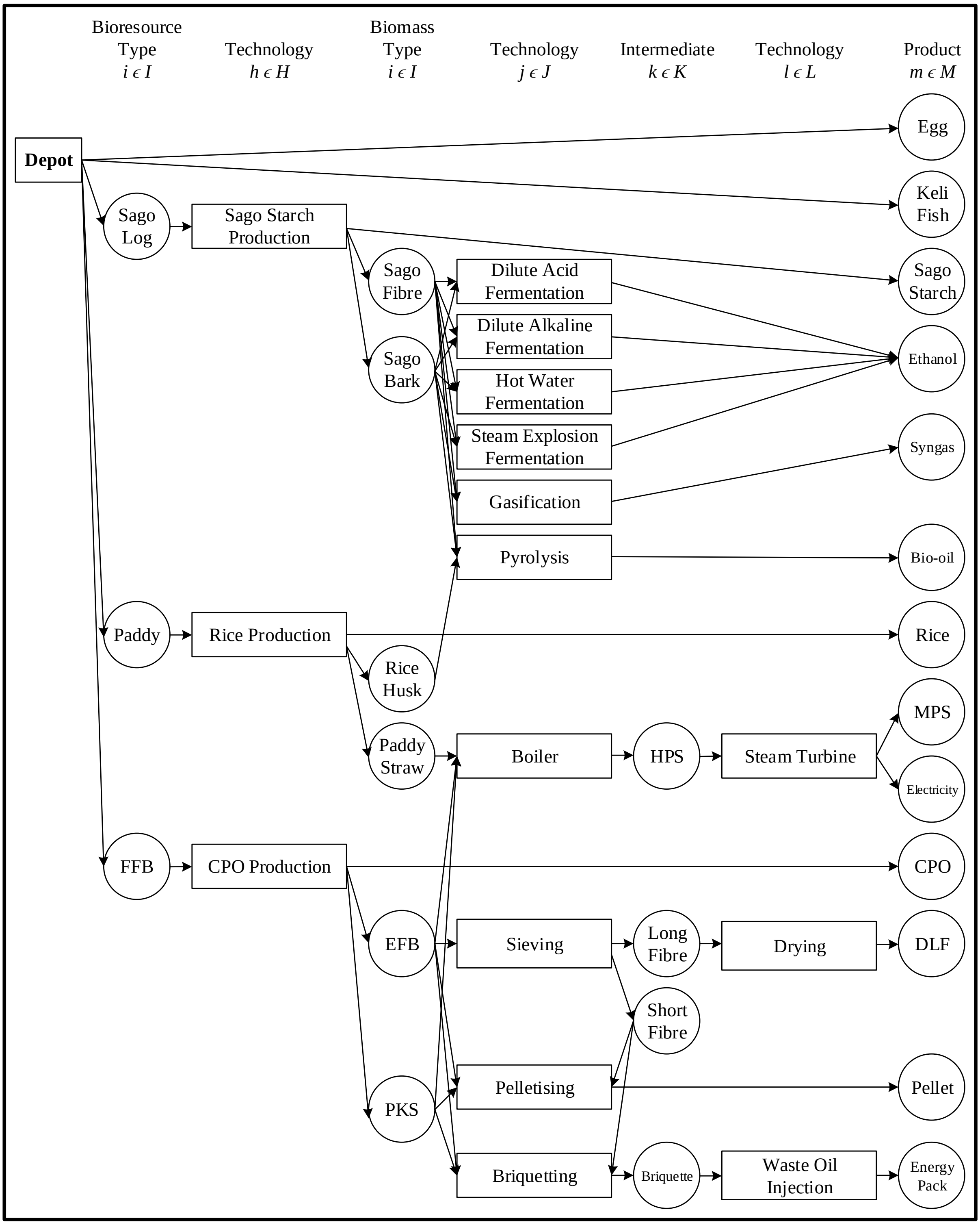

Figure 6-7: Superstructure of case study

As a matter of choice, combusting oil palm-based biomass can generate high pressure steam. Generated high pressure steam can be used for electricity generation. Lastly, eggs and catfishes collected at depot can be sold instantaneously as final product. Note that the conversion and cost of aforementioned technologies are tabulated in *Table 6-1* and *Table 6-2*. The data obtained is fed into extended MBC to determine the optimum processing network.

Table 6-1: Conversion of respective technologies

Technology	**Product**	**Conversion Factor**
Crude Palm Oil Production	Crude Palm Oil	0.23 t/t Fresh Fruit Brunch[1]
	Fresh Fruit Brunch	0.55 t/t Fresh Fruit Brunch[1]
	Palm Kernel Shell	0.22 t/t Palm Kernel Shell[1]
Rice Production	Rice	0.64 t/t Paddy[2]
	Paddy Straw	0.21 t/t Paddy[2]
	Rice Husk	0.15 t/t Paddy[2]
Sago Starch Production	Sago Starch	0.24 t/t Sago Log[3]
	Sago Fibre	0.15 t/t Sago Log[3]
	Sago Bark	0.61 t/t Sago Log[3]
Boiler	High pressure steam	2.59 t/t Empty Fruit Brunch[1]
		3.95 t/t Palm Kernel Shell[1]
		3.83 t/t Paddy Straw[2]
Steam Turbine	Electricity	0.58 Kw/t High Pressure Steam[1]
	Medium pressure steam	0.91 t/t High Pressure Steam[1]
Dehydration	Dried long fibre	0.56 t/t Wet Long Fibre[1]
Separation and sieving	Wet short fibre	0.24 t/t Empty Fruit Brunches[1]
	Wet long fibre	0.67 t/t Empty Fruit Brunches[1]
Pelletising	Pellet	0.33 t/t Wet Short Fibre[1]
		0.33 t/t Palm Kernel Shell[1]
Briquetting	Briquette	0.33 t/t Wet Short Fibre[1]
		0.33 t/t Palm Kernel Shell[1]
Waste oil injection	Energy pack	1.15 t/t Briquette[1]
Pyrolysis	Biooil	0.63 t/t Rice Husk[2]
		0.32 t/t Sago Fibre[3]
		0.32 t/t Sago Bark[3]

Table 6-1 (con't): Conversion of respective technologies

Technology	Product	Conversion Factor
Gasification	Syngas	0.23 t/t Sago Fibre[3]
		0.22 t/t Sago Bark[3]
Acid fermentation	Bioethanol	0.14 t/t Sago Fibre[3]
		0.05 t/t Sago Bark[3]
Alkaline fermentation	Bioethanol	0.16 t/t Sago Fibre[3]
		0.05 t/t Sago Bark[3]
Hot water fermentation	Bioethanol	0.18 t/t Sago Fibre[3]
		0.06 t/t Sago Bark[3]
Steam fermentation	Bioethanol	0.18 t/t Sago Fibre[3]
		0.06 t/t Sago Bark[3]

[1]*Lam et al. (2013);* [2]*Brownsort (2009);* [3]*Hong et al. (2018)*

Table 6-2: Cost of respective technologies

Technology	Cost of Production	Revenue
CPO Production[1]	253 USD/t Crude Palm Oil	520 USD/t Crude Palm Oil
Rice Production[2]	210 USD/t Rice	400 USD/t Rice
Sago Starch Production[3]	125 USD/t Sago Starch	390 USD/t Sago Starch
Boiler[1]	2.60 USD/t HPS	6 USD/t MPS
Steam Turbine[1]	0.05 USD/Kw	0.14 USD/Kw
Dehydration[1]	58.3 USD/t Dried Long Fibre	160 USD/t Dried Long Fibre
Pelletising[1]	52.2 USD/t Pellet	140 USD/t Pellet
Briquetting[1]	46.1 USD/t Briquette	120 USD/t
Waste oil injection[1]	2.50 USD/t Energy Pack	10.5 USD/t Energy Pack
Acid fermentation[3]	98.1 USD/t Ethanol	671 USD/t
Alkaline fermentation[3]	94.6 USD/t Ethanol	671 USD/t Ethanol
Hot water fermentation[3]	70.5 USD/t Ethanol	671 USD/t Ethanol
Steam fermentation[3]	63.5 USD/t Ethanol	671 USD/t Ethanol
Pyrolysis[2]	277 USD/t Biooil	397 USD/t Biooil
Gasification[3]	43.8 USD/t Syngas	198 USD/t Syngas

[1]*Lam et al. (2013);* [2]*Brownsort (2009);* [3]*Hong et al. (2018)*

For the logistic network of the supply chain, VRP is applied to obtain the optimum solution. Firstly, demands of villages p $(p = 2,3 \cdots P)$ are transported from depot p_1. Meanwhile, bioresources and food commodities are collected from villages $p\,(p = 2,3 \cdots P)$ and sent to depot p_1. The location of villages and their respective availability and demand are displayed in *Table 6-3*. As p_1 is the depot, the availability of resources and demand is 0. The geographical location of the studied rural region is shown in *Figure 6-8*. The distances between villages are then obtained from Google Map and tabulated as *Table 6-4*. The mode of bulk transportation of these resources is boat. Annually, a total of 200 round trips are assumed. The related information of transportation is shown in *Table 6-5*. The gathered information is then inputted to solve the VRP model and the result is discussed in the following section.

Table 6-3: Location of villages and their respective availability and demand

Village	**Latitude**	**Longitude**	**Availability (t/y)**	**Demand (t/y)**
p_1	2.7345	112.2005	0	0
p_2	2.6849	112.2329	4,120	85
p_3	2.7078	112.2102	4,270	120
p_4	2.7541	112.1887	4,350	98
p_5	2.8381	112.1753	4,520	76
p_6	2.8864	112.1290	4,540	104
p_7	2.8620	112.1622	3,960	82
p_8	2.8201	112.2123	3,940	79

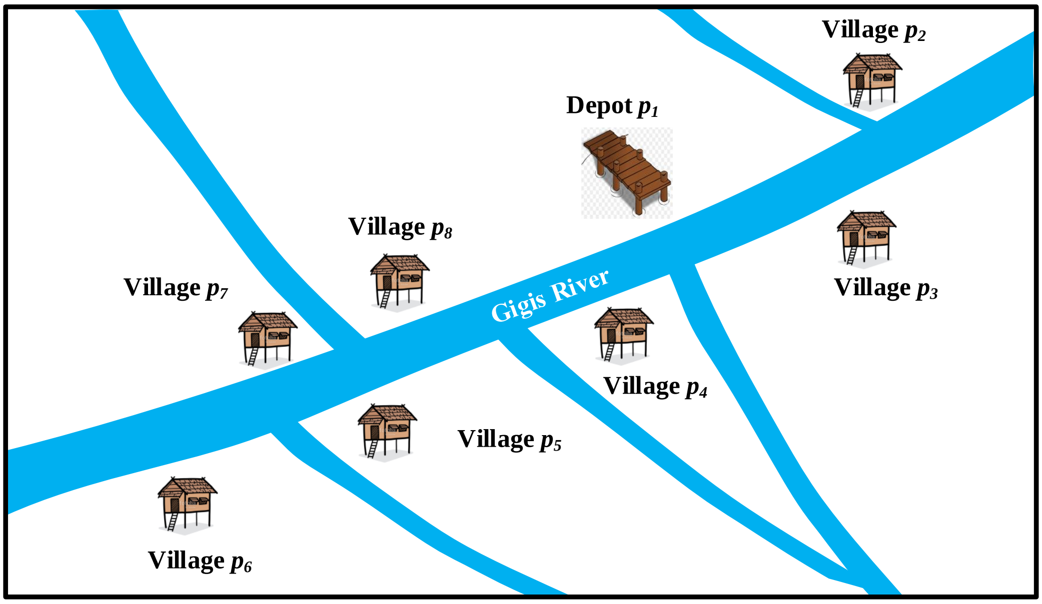

Figure 6-8: Geographical location of studied rural region

Table 6-4: Distances between villages

Location	Distance (km)							
	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8
p_1	0	12	7	5	10	18	16	11
p_2	12	0	6	10	19	26	28	23
p_3	7	6	0	9	18	25	18	18
p_4	5	10	9	0	9	16	10	7
p_5	10	19	18	9	0	7	4	4
p_6	18	26	25	16	7	0	7	9
p_7	16	28	18	7	4	9	0	5
p_8	11	23	18	7	4	9	5	0

Table 6-5: Transportation data

Parameter	Value
Fuel Consumption of Boat	16.2 USD/km
Annualised Capital Cost of Boat	50,000 USD/y
Capacity of Boat	45,000 t/y
Annual Boat Trips	200 trip/y

6.5 Result and Discussion

To generate the optimum processing network for the case study, the extended MBC model is optimised based on Equation 6.9 subject to Equations 6.1 – 6.8. The linear programming (LP) model is solved via a commercial optimisation software LINGO v17.0 with Global Solver. The computational time is about 1s and the resulted model has a total of 35 variables and 22 constraints.

Based on the solution report, the optimum processing structure is extracted and constructed as *Figure 6-9*. As observed from the figure, paddy straw, rice husk, sago log, sago bark, EFB and PKS are produced as biomass from the production of rice, sago starch and palm oil. The biomass is then utilised as renewable feedstock for the generation of biofuel and biochemical. First of all, rice husk and sago bark are feed into pyrolyser to generate biooil. Out of all the fermentation techniques, steam fermentation is selected to transform sago fibre to ethanol. As for paddy straw, it is used to produce power and steam via cogeneration. From the sieving and separation of EFB, long and short fibre are obtained. Both short fibre and PKS can be converted to pellet as solid biofuel. On the other hand, long fibre can be stored and utilised as energy after drying. Together with the eggs and catfishes produced by the villages, these products can generate an annual gross profit AC_{PH}^{GP} of 7.2 million USD.

As an initiative to encourage the biorefinery industry, the Sarawak Corridor of Renewable Energy (SCORE) has been introducing various green policies and schemes on sustainable consumption and production practices. To investigate the effect of these government actions on the structure of the supply chain, a sensitivity analysis is conducted. Two different scenarios are simulated, and the result of the study is tabulated in *Table 6-5*.

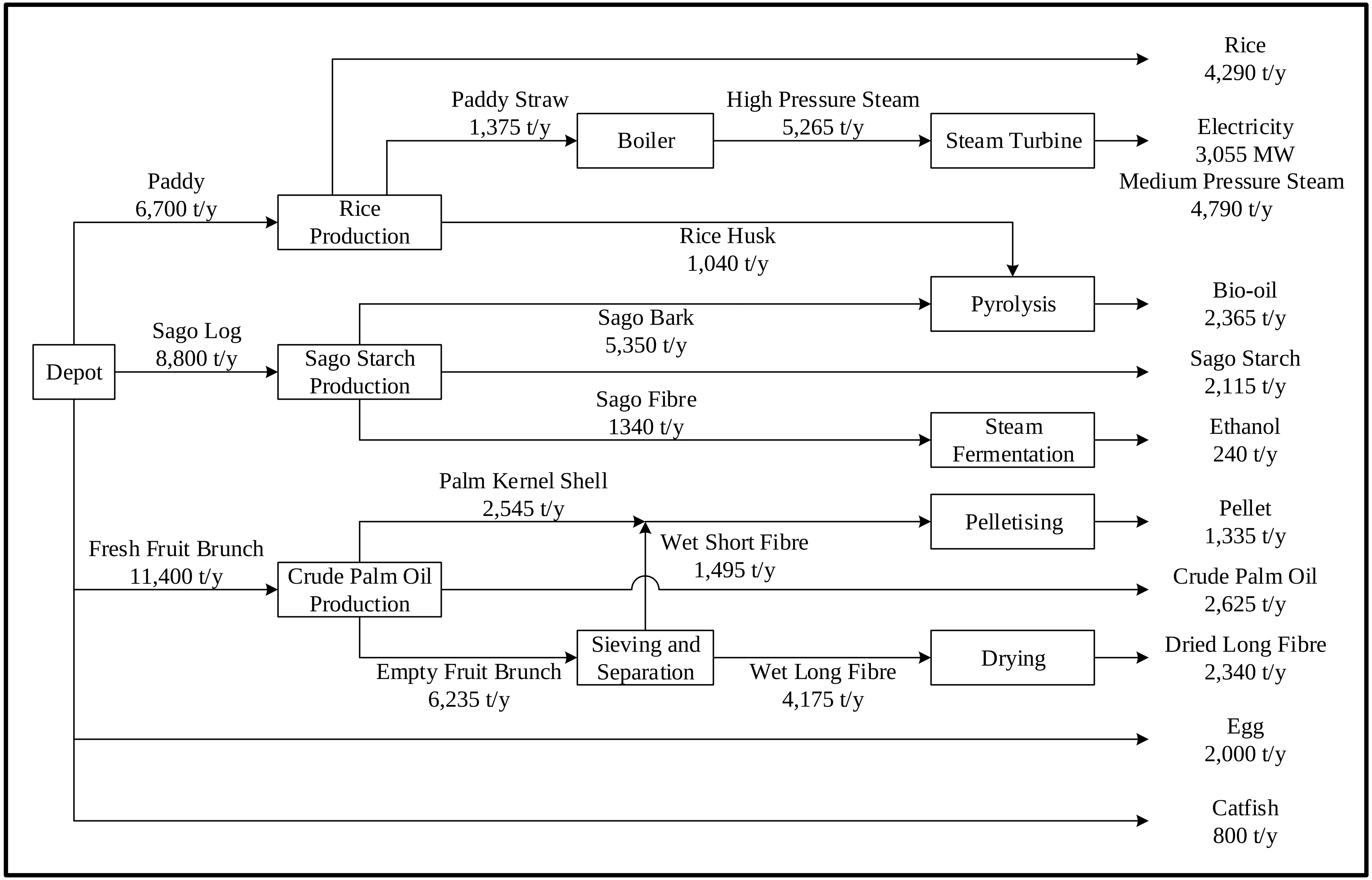

Figure 6-9: Optimum processing network of case study

Table 6-5: Sensitivity Analysis

Scenario	Benefit	Change
Renewable Energy Incentive	20 USD is given to every ton of syngas produced.	Sago bark tends to shift from pyrolysis to gasification.
Green Investment Tax Exemption	75% discount of production cost for acquiring pyrolyser.	Sago fibre tends to shift from fermentation to pyrolysis.

In the first scenario, SCORE introduces renewable energy incentive policy. For every ton of syngas produced, 20 USD is given to the producer as incentive to encourage the commercialisation of green energy. Instead of biooil, sago bark is now being converted into syngas. In the second scenario, the government provides green investment tax exemption as a financial scheme to motive green technology investment. Under this scheme, investing in green technology is tax-free so that the capital cost of pyrolyser is reduced by 75%. As a result, pyrolysis is preferred as the alternative processing technology for sago fibre. The changes in these scenarios are driven by the better economic performance of the processing structure under government policy. This shows that government's efforts have a direct and positive impact towards the biomass industry. Despite existing green policies and schemes, the development of biomass industry in rural areas is stagnant. Government and industry players should work hand in hand to review the current policies and other hidden challenges in the industry.

The VRP model is solved for the optimum logistic network using the same software LINGO v17.0 with Global Solver. The objective function, Equation 6.19 is minimised subject to constraints, Equations 6.10 – 6.19. The resultant MILP model takes about 1s to solve and it contains 57 variables and 74 constraints. Based on the optimum result, the number of boat and the distance travelled are 1 and 58 km respectively. The minimum annual transportation cost

AC^{TR} determined is 691 k USD. The transportation route is displayed in *Figure 6-10*. The boat starts to travel from the depot p_1 to p_8, p_5, p_6, p_7, p_4, p_2, p_3 and then back to the depot. To determine the optimum boat size, the original boat is replaced with 4 other boats of different capacities. Let the original boat be E, the data of other boats is shown in *Table 6-6*. The result obtained from the analysis is presented as a graph as shown in *Figure 6-11*. The optimum routes of boats of different capacities are extracted and displayed in *Figure 6-12*.

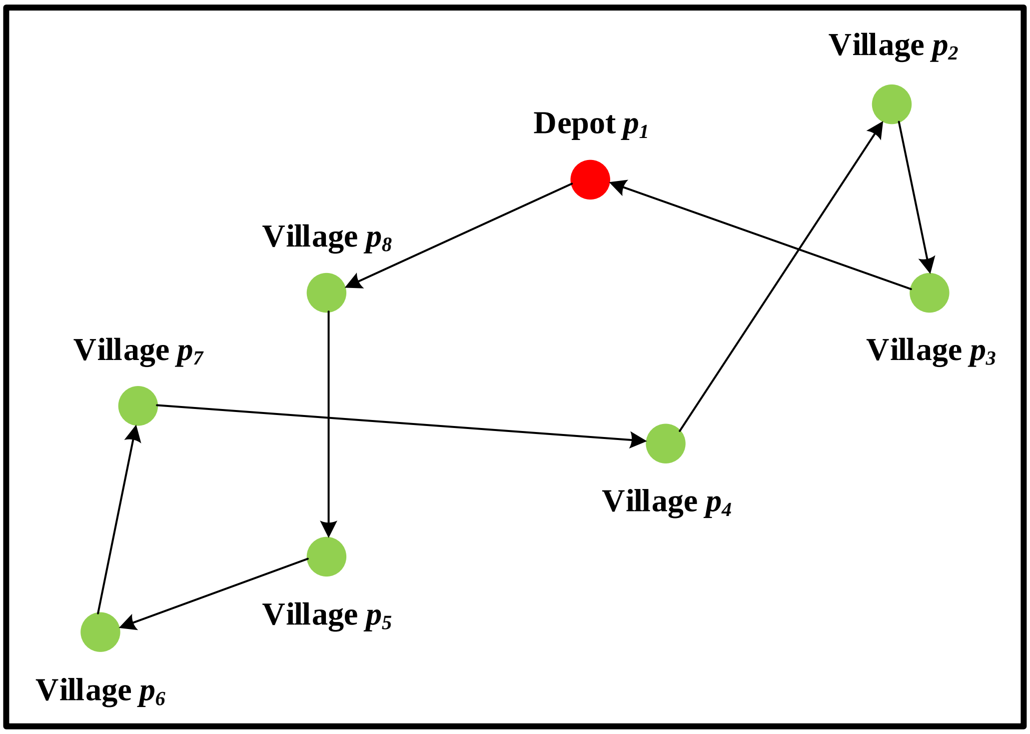

Figure 6-10: The optimum transportation route

Table 6-6: Cost data of boats of different capacities

Boat	Capacity (t/y)	Annualised Capital Cost (USD/y)	Fuel Consumption (USD/km)
A	9000	13,500	8.1
B	18,000	24,500	10.77
C	27,000	34,000	12.5
D	36,000	45,000	14.3

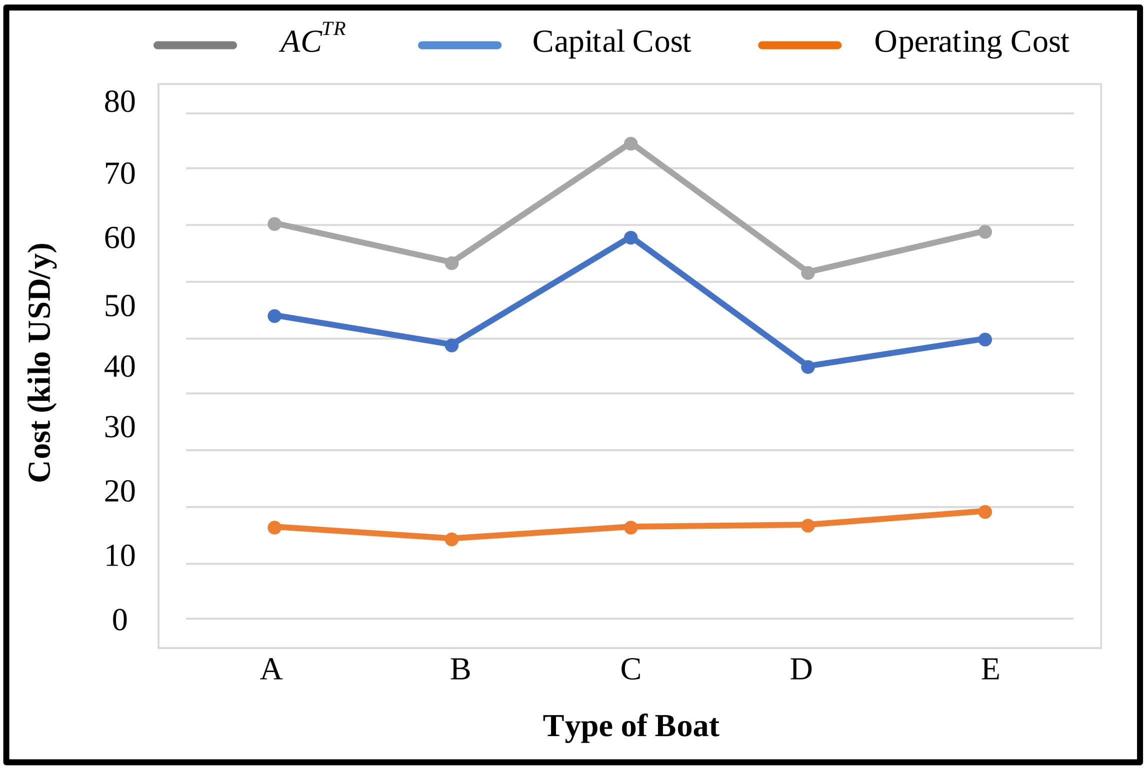

Figure 6-11: Annualised transportation costs of boat with different capacities

In this case study, the optimum boat is boat D with AC^{TR} of 619 k USD as shown in the *Figure 6-11*. Although its fuel consumption ranks the second highest, the higher operating cost is compensated by the lower capital cost. With the same number of boat and distance travelled, boat E incurs a higher capital cost and fuel consumption as compared to boat D because it is considered as oversized for cargo of capacity of 29,700 t/y. The capacity of boat D is equivalent to the load of 2 B boats but utilising 2 boats cost higher in terms of capital investment. Despite lower fuel consumption, the lower operating cost does not outweigh the capital investment for 2 boats. Overall, using boat B costs a higher annual logistic cost as compared to boat D. Similarly, selecting boat A, which has the lowest fuel consumption, as the mode of transportation does not cost lesser as compared to boat B and D due to higher cost of procuring 4 boats. In addition, the longest travel distanced offsets its advantage of having low fuel consumption. Boat C is the least economical, as acquiring two oversize boats result in a spike in the capital expenditure which makes the operating cost no longer a dominant factor. This result of the analysis shows that the optimum boat size is highly depending on the capital cost, fuel consumption, distance travelled and boat number, which tallies and corresponds to Equation 6.17.

It is noticed in *Figure 6-12* that boat D takes a different route as compared to the boat E though both scenarios travel the same distance by utilising only 1 boat. In fact, the total distance travelled of both the scenarios is the same. What makes the route seems different is the direction of travel. The first village that the boat E travels to is p_8, whereas the ending village is p_3. As for boat D, it is completely in a reverse sequence. The same phenomenon is also observed in the scenarios of utilising boat B and boat C as shown in *Figure 6-11*. This proves that the model does not take the direction into account. What matter the most is the total distance travelled. Hence, the distance and the route should be the same for the cases of identity vehicle number, but the direction may vary.

After identifying the optimum boat size, Equation 6.20 is solved and the annualised gross profit AC^{GP} of the supply chain calculated is 6.58 million USD. This case study has successfully demonstrated the application of RIN and it proves that rural biomass supply chain has actually had its own economic value. Therefore, stakeholders in the industry should pay more attention to rural biomass supply chain.

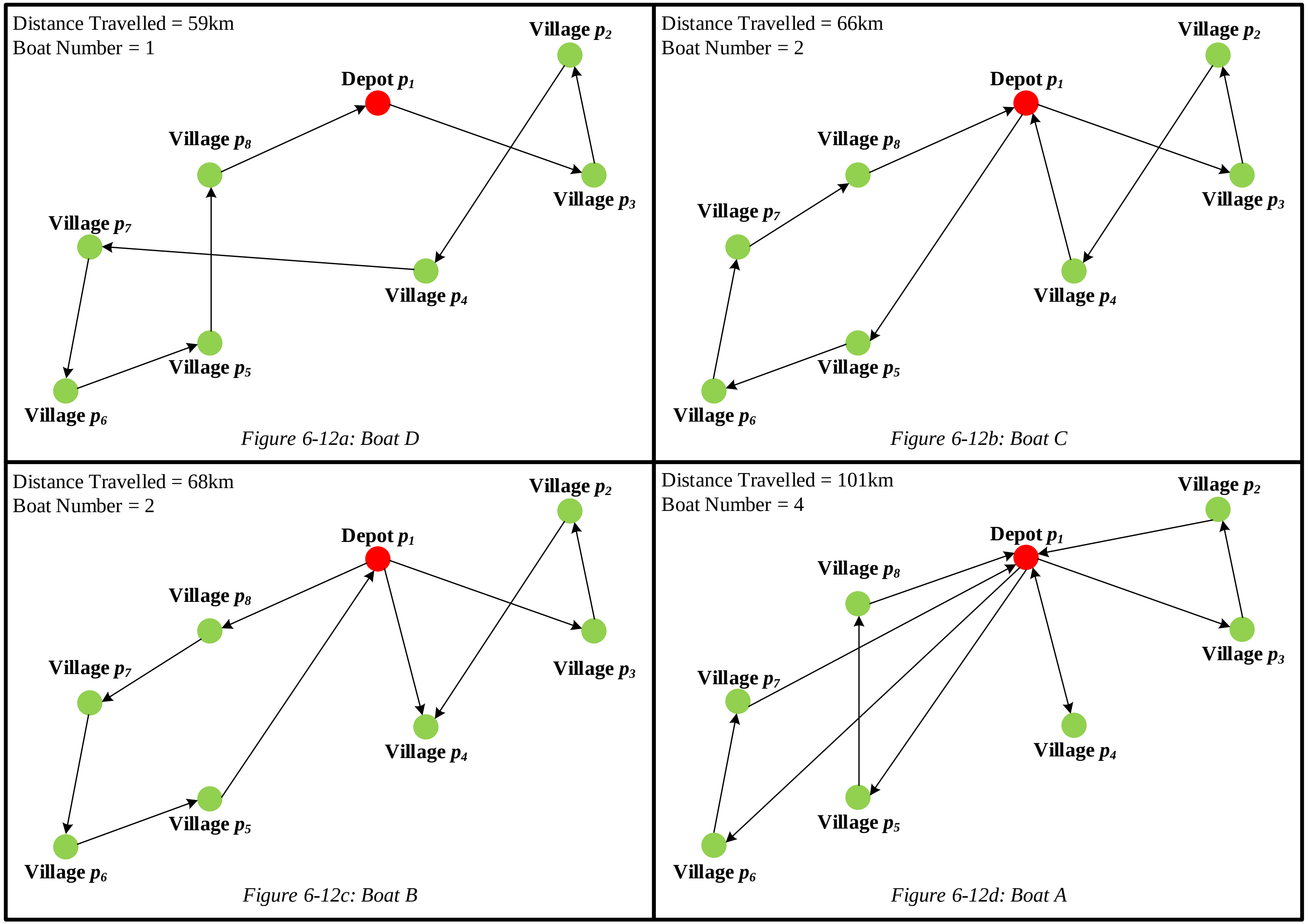

Figure 6-12a: Boat D

Figure 6-12b: Boat C

Figure 6-12c: Boat B

Figure 6-12d: Boat A

Figure 6-12: Optimum routes of boat of different capacities

6.6 Conclusion

In Chapter 5, RIN is proposed for the synthesis of integrated biomass supply chain in rural areas to enhance and diversify rural economy. The approach incorporates food commodities, daily needs and bioresources into the supply chain, utilising water inland transport as the mode of transportation. The methodology extends MBC to solve the processing network. As for logistic network synthesis, VRP is adopted. The framework is successfully illustrated on a case study based on a rural region around Gigis River in Mukah, Sarawak. An optimum processing structure with maximum revenue is determined through an extended MBC. It is discovered that government green schemes are very influential and favourable toward the processing structure and the growth of the industry. To drive the entire industry forward, it is suggested to review the current policies to meet the expectations of stakeholders. VRP, on the other hand, identifies the optimum distance, boat number, travel structure and transportation cost of the supply network. The selection of the optimum boat capacity has also been demonstrated successfully. Hence, this approach can be adopted as a design tool to aid decision makers in establishing an integrated biomass supply chain in rural regions. With the economic potential of the case study calculated, it is concluded that the development of rural integrated biomass supply chain deserves more attention from investors. However, this work is the just the starting point. Authorities and stakeholders should continue to work to together to overcome other barriers along the way (environmental issues, social acceptance and understanding, etc.). Up to this chapter, economic performance is the only indicator used to determine the design of an integrated biomass supply chain. To ensure a sustainable integrated biomass supply chain, all three economic, environmental and social factors should be considered. In the next chapter, sustainability indicator (SI) is introduced to measure the "degree of sustainability" of an integrated biomass supply chain.

CHAPTER 7

FUZZY ANALYTICAL NETWORK PROCESS-BASED (FANP) SUSTAINABILITY ASSESSMENT FRAMEWORK FOR INTEGRATED BIOMASS SUPPLY CHAIN

7.1 Introduction

In response to growing environmental crises and to vast social inequalities in global development, modern societies have adopted sustainability as a leading development model which has become the motivations of government bodies, legislative institutions, industries, corporations and businesses in policy-making and strategic decision-making. These issues have radically changed the way how decisions, which were previously focused on economic aspects, are made such that environmental and social impacts are simultaneously addressed. In line with global efforts in sustainable development, a sustainable integrated biomass supply chain design is needed to ensure industry competitiveness in economic operation, environmental and social performance.

Despite the benefits of using biomass resources as renewable feedstock, economic challenges hinder its intensified use. Biomass has lower energy density than a large number of competing fossil fuels. This results in a costly and complex logistics of procuring, transporting and utilising biomass. Biomass logistic costs typically account for 20-40 % of delivered fuel costs and thus restrict the competitiveness of biomass against other energy sources. As utilisation of biomass for energy generation emits the same amount of carbon that the plants have absorbed while growing, it is considered as a "carbon/climate neutral" fuel source.

However, it requires conventional fuel sources or other raw materials which may have an adverse impact on the environment along the integrated biomass-to-bioproducts supply chain. Besides, large-scale production of bioproducts can potentially cause positive or negative impacts on the society.

It is noted that the vagueness associated with these issues have been overwhelming not to mention difficult to quantify and measure. To address this issue, a fuzzy analytical network process-based (FANP) sustainability assessment framework is proposed to aid decision makers to understand and analyse the economic, environmental and social impacts of integrated biomass supply chains. This understanding is required to mitigate undesirable impacts, increase the benefits associated with biomass utilisation, and ensure the sustainability of new projects that attract community, government and investors′ interest and support. In this work, an illustrative case study is presented to demonstrate the proposed assessment tool.

7.2 FANP as a Sustainability Assessment Tool

Sustainability assessment is defined as *"a generic term for a methodology that aims to assist decision-making by identifying, measuring and comparing the social, economic and environmental implications of a project, program, or policy option".* The main goals of sustainability assessment are stated as follows: (i) an input to strategic planning and decision-making, (ii) information for monitoring, evaluation and impact analysis of any policy, strategy or initiative, (iii) a source for reporting on the state of the environment and (iv) a process to raise awareness about sustainability issues.

Among sustainability assessment methods, the indicator-based approach is the most promising in terms of transparency and usefulness to the decision-making process. The strength of sustainability indicators lies in providing better simplification, quantification, analysis and communicating information from the perspectives of the triple bottom-line. Sustainability indicators are based on measured or estimated data that must undergo normalisation, scaling and aggregation. The aggregation process is usually carried out by computing a sustainability index (SI), a single score that represents aggregation of multiple indicators using weight-based mathematical methods. The SI synthesised is used as an assessment model aiming to quantify the sustainability performance of integrated biomass supply chain (López and Monzón, 2010).

The normalisation and scaling processes involve placing a relative weigh to each of the sustainability indicator. Multi-criteria decision analysis (MCDA) tools such as weighted sum model (WSM), analytical hierarchical process (AHP) and max-min aggregation approach are the commonly used normalisation and scaling tools. However, a major limitation in these approaches is the incapability to consider the interactions among the sustainability indicators. Owing to the multifaceted nature of sustainability indicators, the entire assessment process is complex and difficult to specify precisely. In most cases, these indicators are conflicting and dependent on each other. Besides, the economic, environmental, and social indicators for integrated biomass supply chain are different in terms of how stakeholders perceive them. Thus, it is necessary to determine the importance of the individual indicator, their inter-relationships with one another and their effect on the overall SI.

Therefore, this work adopts Analytic Network Process (ANP) to incorporate the interactions among sustainability indicators into the SI. The ANP is the generalised form of AHP which is proposed to overcome the limitation of the AHP's linear hierarchy structure

(Saaty, 1986). Similar to AHP, the ANP framework consists of 3 basic features which are tabulated in *Table 7-1*.

Table 7-1: The features of AHP and ANP

Features	AHP	ANP
Structuring and modelling system's complexity	Single-directional hierarchical model with the assumption of mutual independence of elements	Multi-directional and non-linear network structure of interdependence and feedback
Measuring on a ratio scale	Local priorities derived from pairwise comparison matrices	Local priorities derived from pairwise comparison matrices
Synthesising	Overall priorities from hierarchic composition	Overall priorities from supermatrix calculations

As compared to AHP, the ANP framework is more comprehensive in MCDA as it allows both interaction and feedback within clusters of elements and between clusters. The feedback feature captures the complex effects of interconnection in human society, especially when risk and uncertainty are involved. The main objective in the process is to determine the overall influence of all elements in conjunction with each other (Saaty, 2004). *Figure 7-1* displays the structural difference between AHP and ANP. As shown in the figure, the main feature of ANP is its underlying problem structure represented as a strongly connected hierarchical network to understand the complexity of selection problem. On the other hand, AHP is the simple and special case of an ANP and it ignores all the interdependence and feedback relation between clusters and shown only the linear hierarchical structure. The flexibility that ANP offered in structuring the problem and converting subjective judgements into objective measure has enabled a wide range of application, both in the research and business arena (Sipahi & Timor, 2010).

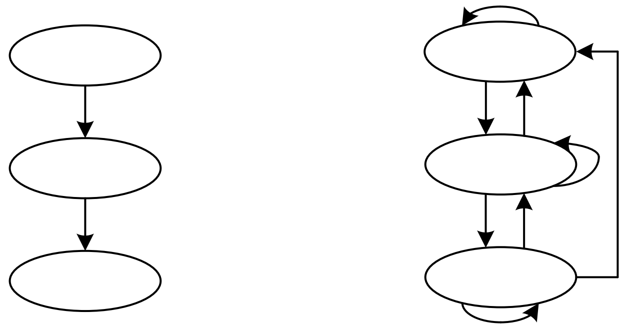

Figure 7-1a: AHP Structure *Figure 7-1b: ANP Structure*

Figure 7-1: Structural representation of AHP and ANP

In conventional ANP, pairwise comparison is used to represent the relative importance between elements which is mathematically simple and flexible (Saaty, 1980). A great drawback of this method is that pairwise judgement consists of deterministic comparisons, but the real world has an indeterminate nature (Promentilla et al., 2008). It is unable to capture the vagueness and ambiguous in human decision and judgement. As a result, fuzzy set theory is incorporated with AHNP to capture the fuzziness and uncertainties during value judgment elicitation. Fuzzy set theory is first introduced to overcome constraints of limited information and data (Zadeh, 1965). It is later applied to aid decision-makings, particularly those associated with personal or subjective opinions that involve high degree of uncertainty and imprecision. Fuzzy set theory is integrated with ANP by replacing the crisp input for pairwise comparison with fuzzy membership function. Fuzzy membership function does not only enable the level of dominance relationship to be implied more precisely with the inclusion of upper and lower bound, the range of lower bound and upper bound also indicates the confidence level of experts in giving such judgements (Tan et al., 2014). The following section discusses the FANP-based assessment framework in detail.

7.3 Methodology

The methodology of FANP-based assessment framework is illustrated in *Figure 7-2*. First of all, the ultimate goal of this work is to synthesise a SI as an assessment tool to measure the performance of integrated biomass supply chain. However, the SI is made up of multiple economic, environmental and social indicators which are affected by different factors for different contexts. Therefore, the goal of the work must be defined specifically to meet the requirement in different cases. In the next stage, factors which affect the goal are identified. They are selected based on the nature of the industry and predilection of stakeholders.

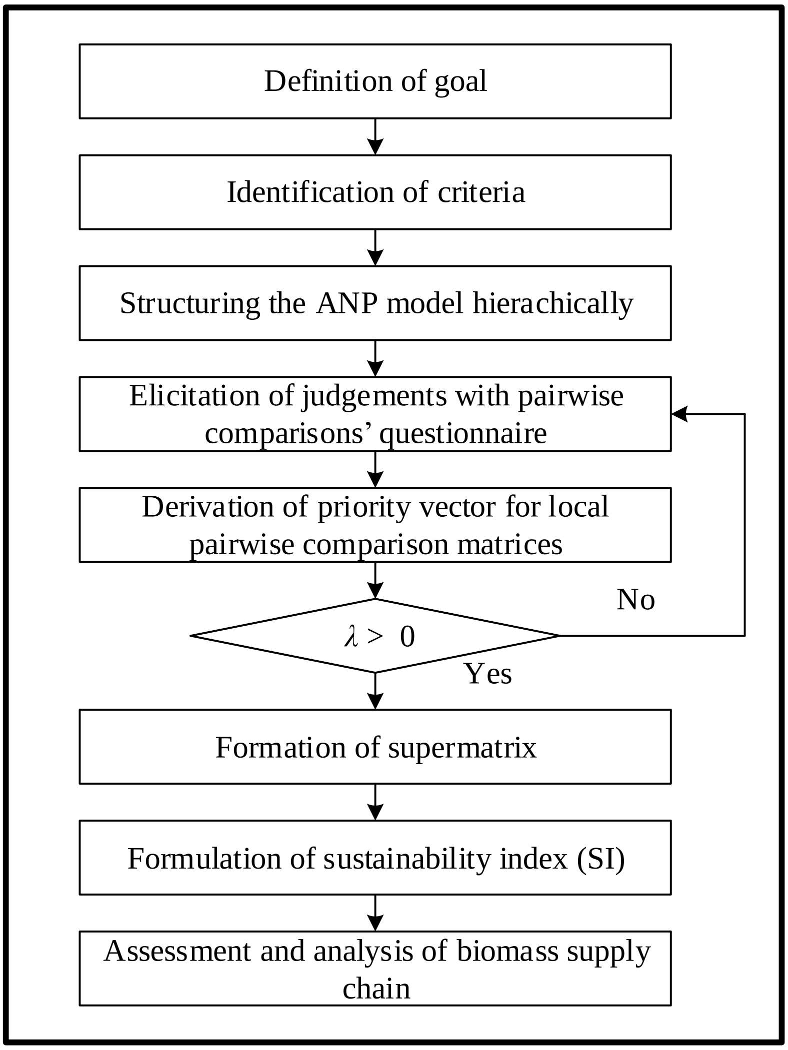

Figure 7-2: FANP-based sustainability assessment framework

Thirdly, ANP model structuring consists of two steps which are clustering and connecting. In the first step, a number of clusters are formed with respect to the criteria identified. These criteria are then assigned to the clusters to which are mostly related. In the second step, the related clusters are connected hierarchically with different arrows to represent the relationship of the clusters and criteria within clusters. A general three-level decision structure and its supermatrix is illustrated in *Figure 7-3*. The 3 clusters include goal cluster (A), evaluation criteria cluster (B) and evaluation sub-criteria cluster (C). The directed structural model of the hierarchical network shown is strongly connected by arrows which can be interpreted as the flow of influence in the system. *Table 7-2* summarises the relationship of these arrows to the blocks of the supermatrix as shown in *Figure 7-3*.

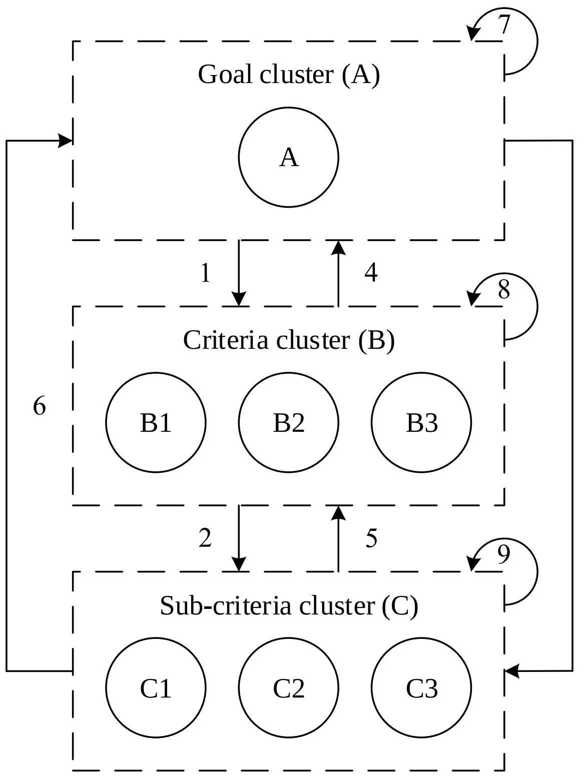

Figure 7-3a: General hierarchical network model

	Goal	Criteria	Sub-criteria
Goal	AA	AB	AC
Criteria	BA	BB	BC
Sub-criteria	CA	CB	CC

Figure 7-3b: General supermatrix

Figure 7-3: A sample of general hierarchical network model and its supermatrix

Table 7-2: Relationship between arrows of the network and blocks of supermatrix

Arrow	Block	Interpretation of Dependence
1	BA	Direct dependency of B with respect to A with priority vector BA
2	CB	Direct dependency of C with respect to B with priority vector CB
3	CA	Direct dependency of C with respect A with priority vector CA
4	AB	Feedback dependency of A with respect to B with priority vector AB
5	BC	Feedback dependency of B with respect to C with priority vector of BC
6	AC	Feedback dependency of A with respect to C with priority vector AC
7	AA	Inner dependency of criteria within A with priority vector AA
8	BB	Inner dependency of criteria within B with priority vector BB
9	CC	Inner dependency of criteria within C with priority vector CC

In the fourth stage of the framework, pairwise comparisons are performed among the criteria and clusters via questionnaire. The nature of ANP method for relative measurement based on the knowledgeable and experts do not always require statistically significant sample size. Depending on the subject matter, a minimum number of 2 domains that well-represent the group of decision makers or industry stakeholders is admissible. Given a control criterion, experts are required to compare the dominance relationship between two criteria. It is noted that the dominance relationships can be interpreted as importance, preferences, likelihood or influence of one criterion to the other criterion with respect to a controlling criterion. Linguistic scale with triangular fuzzy numbers (TFN) is adopted as the intensity assigned to the comparison between criteria. The set of linguistic scale and its respective triangular fuzzy number presented in *Table 7-3* aims to account for uncertainties and degree of confidence in the judgment of stakeholders (Promentilla et al., 2016). This fuzzy scale follows the Fibonacci sequence where the degree of fuzziness increased with the intensity of dominance relationship (Orbecido et al.,2016). The group fuzzy judgment $\hat{\mathrm{z}}_{st} = \langle \mathrm{l}_{st}, \mathrm{m}_{st}, \mathrm{u}_{st} \rangle$ is computed from the aggregation of individual judgements of U decision makers using the geometric mean method (Dong et al., 2010) as stated as follows.

$$\mathrm{L}_{st} = \left(\prod_{u=1}^{U} (\mathrm{l}_{st})^{\mathrm{v}_u}\right);\ \mathrm{m}_{st} = \left(\prod_{u=1}^{U} (\mathrm{m}_{st})^{\mathrm{v}_u}\right);\ \mathrm{u}_{st} = \left(\prod_{u=1}^{U} (\mathrm{u}_{st})^{\mathrm{v}_u}\right) \quad (7.1)$$

where l_{st}, m_{st}, and u_{st} represent the lower bound, mode and upper bound of the pairwise comparison of criteria *s* to *t* respectively, and v_u is the influence weight of stakeholder *u*. The computed $\hat{\mathrm{z}}_{st}$ is then used as entry to the reciprocal pairwise comparison matrix $\hat{\mathrm{Z}}$ as follows.

$$\hat{\mathrm{Z}} = \begin{bmatrix} \langle 1,1,1 \rangle & \hat{\mathrm{z}}_{12} & \cdots & \hat{\mathrm{z}}_{1T} \\ \hat{\mathrm{z}}_{21} & \langle 1,1,1 \rangle & \cdots & \hat{\mathrm{z}}_{2T} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{\mathrm{z}}_{S1} & \hat{\mathrm{z}}_{S2} & \cdots & \langle 1,1,1 \rangle \end{bmatrix} \quad (7.2)$$

$$\hat{\mathrm{z}}_{st} = \frac{1}{\hat{\mathrm{z}}_{st}} = \langle \frac{1}{\mathrm{u}_{st}}, \frac{1}{\mathrm{m}_{st}}, \frac{1}{\mathrm{l}_{st}} \rangle \quad (7.3)$$

Table 7-3: Fuzzy scale for pairwise comparative judgement

Linguistic Scale	**Triangular fuzzy scale $\langle \mathbf{l}_{fg}, \mathbf{m}_{fg}, \mathbf{u}_{fg} \rangle$**
Equally	$\langle 1.0, 1.0, 1.0 \rangle$
Slightly more	$\langle 1.2, 2.0, 3.2 \rangle$
Moderately more	$\langle 1.5, 3.0, 5.6 \rangle$
Strongly more	$\langle 3.0, 5.0, 7.9 \rangle$
Very strongly more	$\langle 6.0, 8.0, 9.5 \rangle$

Fifthly, the priority vectors, w_y for pairwise comparisons matrices $\hat{\mathrm{Z}}$ are derived by adjusting solution ratios, z_{st} and z_{ts} to maximise the consistency index, λ.

$$Maximise\ \lambda \quad (7.4)$$

The λ can be defined as the degree of membership in a membership function of TFN that measures the degree of satisfaction of all computed pairwise comparison ratios to satisfy the initial fuzzy judgements (Promentilla, 2014). A positive λ indicates a consistent fuzzy pairwise comparison matrix wherein $\lambda = 1$ suggests perfect consistency in preserving the order of preference intensities. In the event where λ is negative value, it is suggested for the respective stakeholders to revise their pairwise comparison judgements (Tan et al., 2014). The λ is influenced by the stakeholders' pairwise comparison ratio z_{st} and z_{ts} which in turn must be approximately equal to the fuzzy value elicited from expert as shown as follows.

$$\frac{z_{st} - \mathrm{l}_{st}}{\mathrm{m}_{st} - \mathrm{l}_{st}} \geq \lambda \qquad \forall s = 1, \cdots, S-1; t = s+1, \ldots, T \tag{7.5}$$

$$\frac{\mathrm{u}_{st} - z_{st}}{\mathrm{u}_{st} - \mathrm{m}_{st}} \geq \lambda \qquad \forall s = 1, \cdots, S-1; t = s+1, \ldots, T \tag{7.6}$$

$$\frac{z_{ts} - \mathrm{l}_{st}}{\mathrm{m}_{st} - \mathrm{l}_{st}} \geq \lambda \qquad \forall t = 1, \cdots, T-1; s = t+1, \ldots, S \tag{7.7}$$

$$\frac{\mathrm{u}_{st} - z_{st}}{\mathrm{u}_{st} - \mathrm{m}_{st}} \geq \lambda \qquad \forall t = 1, \cdots, T-1; s = t+1, \ldots, \tag{7.8}$$

To increase the value of λ, Equations 7.5 – 7.8 will tend to push z_{st} and z_{ts} toward the most plausible value of m_{st} and m_{ts}. Therefore, the pairwise comparison ratio z_{st} is equivalent to the ratio of priority vector w_s and w_t. Similar to z_{st}, the formulation of z_{ts} are stated as follows.

$$z_{st} = \frac{w_s}{w_t} \qquad \forall s = 1, \cdots, S-1; t = s+1, \ldots, T \tag{7.8}$$

$$z_{ts} = \frac{w_t}{w_s} \qquad \forall t = 1, \cdots, T-1; s = t+1, \ldots, S \tag{7.9}$$

The value of individual w_y must be non-zero. Besides, the sum of the all the priority vectors is equal to 1 as defined as follows.

$$w_y > 0 \qquad \forall y \in Y \tag{7.10}$$

$$\sum_{y=1}^{Y} w_y = 1 \qquad \forall y \in Y \tag{7.11}$$

In the sixth step, the priority vectors derived are arranged according to the hierarchical network model to form an unweighted supermatrix as shown in *Figure 7-3b*. There are two types of dependency relationship between clusters and within cluster. Independence relationship take place when there is no direct relationship between two clusters or elements within a cluster only depend on itself, resulting in an identity matrix in the block matrix. While interdependence relationship applies when two clusters are related or elements within a cluster are interacting with each other. The detailed discussion of the relationship between the ANP network and supermatrix has been done and presented in *Table 7-2*.

The initial supermatrix is not necessarily column stochastic, which means all columns do not sum to 1. Through cluster weighting and normalisation of the unweighted supermatrix, the resulted column stochastic matrix is the weighted supermatrix. To integrate all the possible interaction and movement of the elements in the model, the supermatrix is powered until it converges and stabilise to a unique value. The resulted values are the limiting values which indicates the final priority weightages of criteria. The sustainability index (SI) is determined by the integration of individual criteria its final priority weightage.

$$SI = \sum_{y=1}^{Y} w_y S_y \qquad \forall y \in Y \qquad (7.12)$$

where S_y is the score for individual criterion and w_y is the priority weightage assigned for each criterion with FANP.

Lastly, the synthesised SI can be utilised to analyse and assess the sustainability performance of integrated biomass supply chain. This framework aids stakeholders within the value chain to understand the sustainability performance of the entire system, easing decision-making. This allows mitigation of undesired impacts and intensification the positives of biomass utilisation which attract more attention from public and society to the industry. The proposed framework is demonstrated with an illustrative example in the next section.

7.4 Case Study

The development of sustainable integrated biomass supply chain is often complex, multi-dimensional. It may involve different stakeholders with different preferences and objectives. As different stakeholders have different perspective towards sustainability of integrated biomass supply chain, the goal of the case study is to determine prioritisation of sustainability indicators by stakeholders in the formation of SI for the assessment and analysis of integrated biomass supply chain. The ANP model is structured based on stakeholders to understand the priority of sustainability indicators by individual stakeholder as an overall industry. The model consists of 3 levels. The top level is the goal, followed by level 2, stakeholders and level 3, sustainability indicators. The elements within each cluster are identified and they are represented by different symbols as shown in *Table 7-4.* The 3-level ANP model is constructed based on the elements identified as displayed in *Figure 7-4*.

Table 7-4: Goal, stakeholders and sustainability indicators with respective symbol

Level	Element	Symbol
1	Goal	GO
2	Government	S1
	Industry Player	S2
	Investor	S3
	Researcher	S4
3	Gross Profit	C1
	Carbon Footprint	C2
	Water Footprint	C3
	Land Footprint	C4
	Processing Hub Inherent Safety	C5
	Transportation Safety	C6
	Job Creation	C7

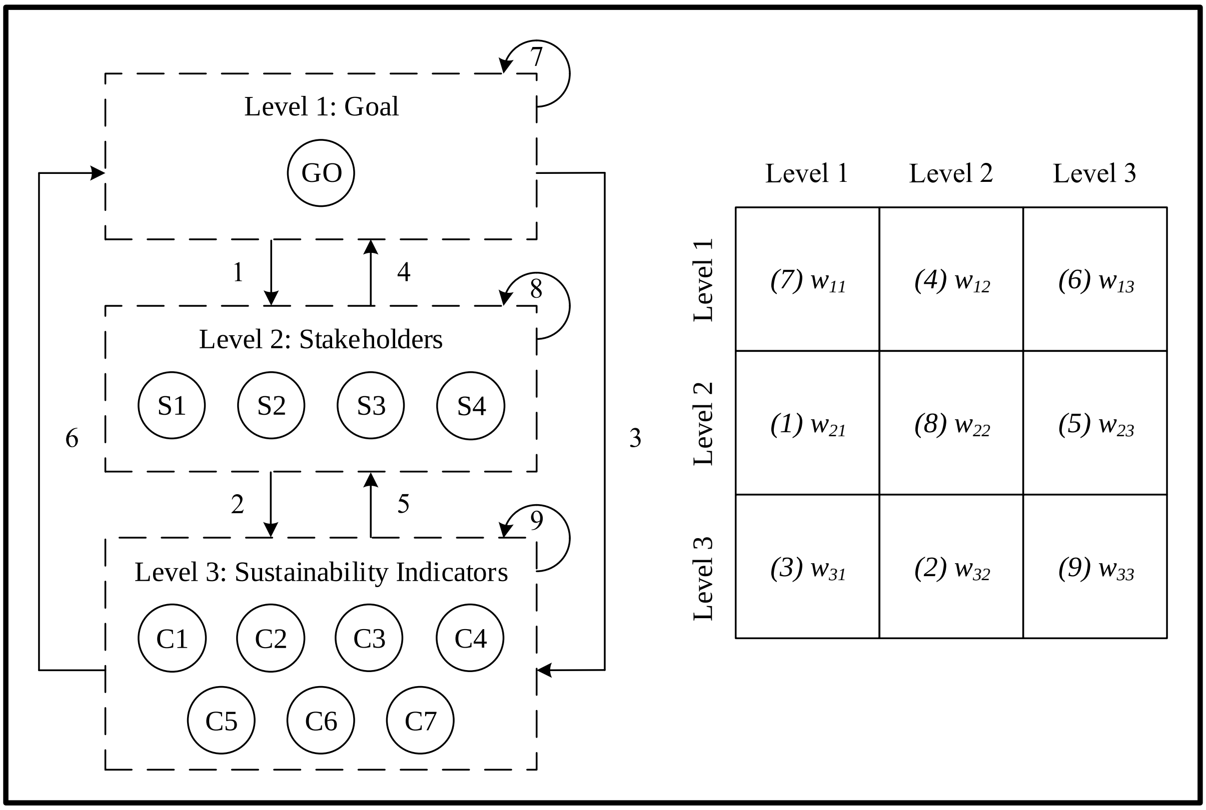

Figure 7-4: Diagraph of hierarchical network model and its supermatrix

As the highlight of this work is to incorporate subjective judgements of expertise and experience personnel of biomass industry for both qualitative and quantitative sustainability indicators to form a comprehensive set of sustainability index, more emphasis is put on the demonstration of the FANP-based framework in deriving priority weights for sustainability indicators. The explanation and calculation of sustainability indicators will be discussed in the next chapter. Next, a group of biomass industry stakeholders from West Malaysia (K=4) is invited to response to the pairwise comparison questionnaires through email. Individual judgement is extracted from the survey to form a group fuzzy judgement through Equation 7.1. The computed fuzzy judgement is then used as entry to the reciprocal pairwise comparison matrix as Equations 7.2 – 7.3. Equations 7.4 – 7.11 are solved as a non-linear programming (NLP) model via Lingo 17.0 to determine the priority vectors of each fuzzy local priority matrix. The priority vectors are populated to form the initial supermatrix as shown in *Table 7-5*.

Table 7-5: Initial supermatrix

	Goal	S1	S2	S3	S4	C1	C2	C3	C4	C5	C6	C7
Goal	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
S1	0.4761	1.0000	0.4827	0.5675	0.5447	0.2920	0.1506	0.1047	0.1146	0.0973	0.3315	0.4046
S2	0.1014	0.1764	1.0000	0.1861	0.1856	0.2806	0.4149	0.3060	0.3254	0.3327	0.3430	0.2410
S3	0.2483	0.3838	0.2643	1.0000	0.2697	0.1646	0.1686	0.1417	0.1451	0.3435	0.2215	0.2775
S4	0.1742	0.4398	0.2530	0.2464	1.0000	0.2628	0.2659	0.4476	0.4149	0.2265	0.1040	0.0769
C1	0.3940	0.3636	0.4139	0.4362	0.3067	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C2	0.1212	0.1409	0.0713	0.1425	0.1730	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C3	0.0779	0.0728	0.0713	0.0720	0.0975	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000
C4	0.0518	0.0523	0.0469	0.0462	0.0549	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
C5	0.1532	0.1961	0.1088	0.1426	0.1730	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000
C6	0.1135	0.1014	0.1087	0.1143	0.0975	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
C7	0.0884	0.0729	0.1791	0.0462	0.0974	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000

As shown in *Figure 7-4*, all the relationships between clusters and elements are represented by numerical value in bracket to ease the understanding on the arrangement of priority vectors in the initial supermatrix. Self-looping arrows (7), (8) and (9) shows the interdependence relationship between elements within a cluster with priority vectors w_{11}, w_{22} and w_{33}. The priority vector w_{33} shows an identity matrix which means that the sustainability indicators in level 3 are independent of each other. Feedback dependence loop (4) and (6) are the arrows connecting every cluster back to the goal of study. The priority vectors for feedback control loop, w_{12} and w_{13} are unit row vectors $e^T = (1,1,\cdots,1)$, which indicates that the goal is controlling the subsystem and strongly connect with all the clusters as a model. The direct dependence of stakeholders and sustainability indicators with respect to goal is represented by downward arrow (1) and (3) with priority vectors w_{21} and w_{31} respectively. Similarly, the two-way relationships between stakeholder and sustainability indicators are indicated by arrow (2) and (5) with priority vector w_{32} and w_{23}.

The unweighted supermatrix is normalised to achieve column stochastic. To consider all the interactions between clusters, the resulted weighted supermatrix as shown in *Table 7-6* is raised to power until all the values converge to form the limiting values. The limiting values indicating the final priority weightages of all the elements are utilised for pie chart construction as shown in *Figure 7-5.* At this stage, government (35.22%) plays the most important role in encouraging the sustainable growth of the entire industry via its governance regime and policy as shown in *Figure 7-5a*. Financiers (23.37%) and researchers (22.66%) play moderate but equally important role to provide financial and technical supports respectively to encourage the sustainable development of biomass industry. As the development of sustainable integrated biomass supply chain in Malaysia is still at its preliminary stage, industry players (18.75%) is relatively passive and play the least important role among all stakeholders.

Table 7-6: Weighted supermatrix

	Goal	S1	S2	S3	S4	C1	C2	C3	C4	C5	C6	C7
Goal	0.3333	0.2500	0.2500	0.2500	0.2500	0.3333	0.3333	0.3333	0.3333	0.3333	0.3333	0.3333
S1	0.1587	0.2500	0.1207	0.1419	0.1362	0.0973	0.0502	0.0349	0.0382	0.0324	0.1105	0.1349
S2	0.0338	0.0441	0.2500	0.0465	0.0464	0.0935	0.1383	0.1020	0.1085	0.1109	0.1143	0.0803
S3	0.0828	0.0960	0.0661	0.2500	0.0674	0.0549	0.0562	0.0472	0.0484	0.1145	0.0738	0.0925
S4	0.0581	0.1100	0.0633	0.0616	0.2500	0.0876	0.0886	0.1492	0.1383	0.0755	0.0347	0.0256
C1	0.1313	0.0909	0.1035	0.1091	0.0767	0.3333	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C2	0.0404	0.0352	0.0178	0.0356	0.0433	0.0000	0.3333	0.0000	0.0000	0.0000	0.0000	0.0000
C3	0.0260	0.0182	0.0178	0.0180	0.0244	0.0000	0.0000	0.3333	0.0000	0.0000	0.0000	0.0000
C4	0.0173	0.0131	0.0117	0.0116	0.0137	0.0000	0.0000	0.0000	0.3333	0.0000	0.0000	0.0000
C5	0.0511	0.0490	0.0272	0.0357	0.0433	0.0000	0.0000	0.0000	0.0000	0.3333	0.0000	0.0000
C6	0.0378	0.0254	0.0272	0.0286	0.0244	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.0000
C7	0.0295	0.0182	0.0448	0.0116	0.0244	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333

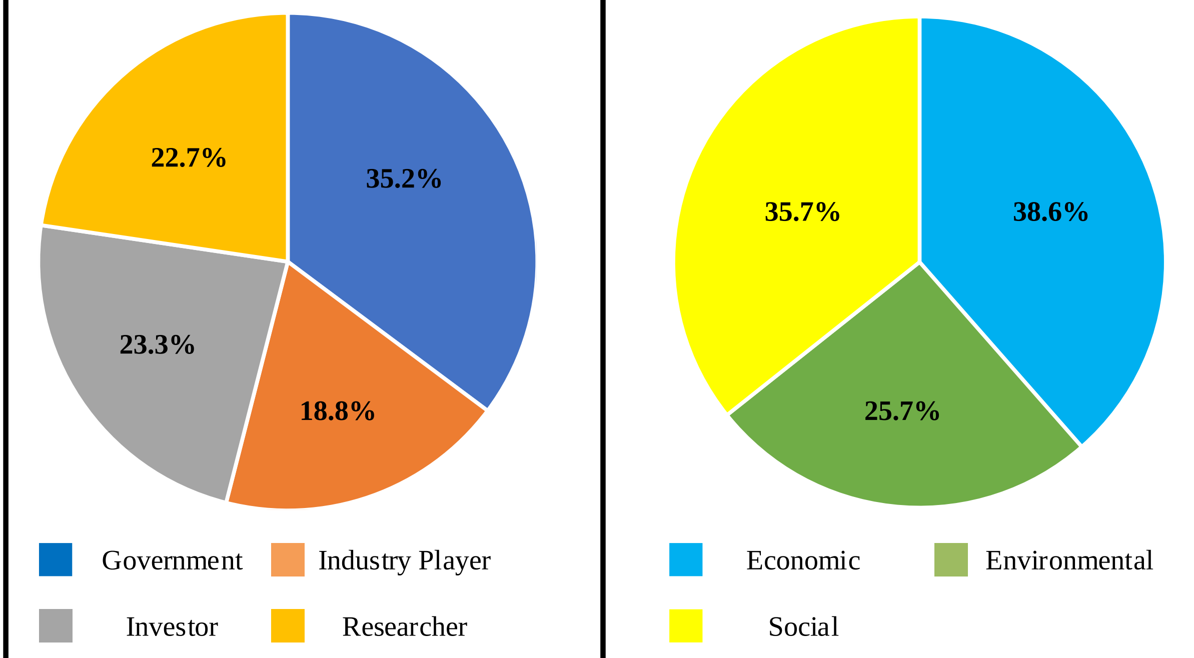

Figure 7-5a: Role of stakeholders in sustainability development of biomass supply chain

Figure 7-5b: Priority weightages of sustainability indicators in the formation of SI

Figure 7-5: The final priority weightages of respective elements of West Malaysia

As shown in *Figure 7-5b*, economic cluster (38.56%) is relatively important in the development of sustainable integrated biomass supply chain in West Malaysia, followed by social impact (35.71%) and environmental impact (25.74%). Gross profit that carries 38.56% is the main driving force for industry stakeholders to ensure the sustainable growth of the industry, followed by processing hub safety (15.76%), carbon footprint (12.83%), transportation safety (10.92%), job creation (9.03%), water footprint (7.79%) and land footprint (5.11%). Based on the result, the weightages are distributed evenly among economic, environmental and social factors. The sustainability awareness in West Malaysia is acceptable. The resultant sustainable index (SI) is stated as follows.

$$SI = 0.3856S_{GP} + 0.1283S_{CF} + 0.0779S_{WF} + 0.0511S_{LF} + 0.1576S_{IS} + 0.1092S_{TS} + 0.0903S_{JC} \qquad (7.13)$$

West Malaysia is relatively more developed as compared to East Malaysia. As different stakeholders from different region and background is likely to have a different perception towards sustainability, the prioritisation of sustainability indicators in the formation of SI varies with different sets of stakeholders. To verify this situation, another group of stakeholders (*K=4*) from East Malaysia is invited to complete the same set of pairwise comparison survey. The same procedures are walked through, and the result is shown in *Figure 7-6*.

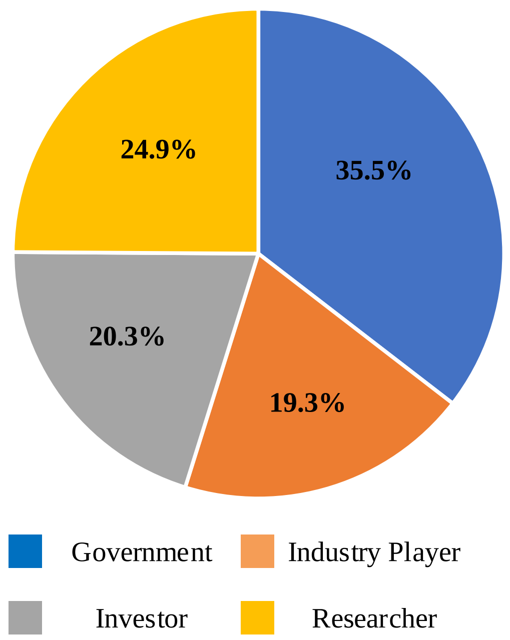

Figure 7-6a: Role of stakeholders in sustainability development of biomass supply chain

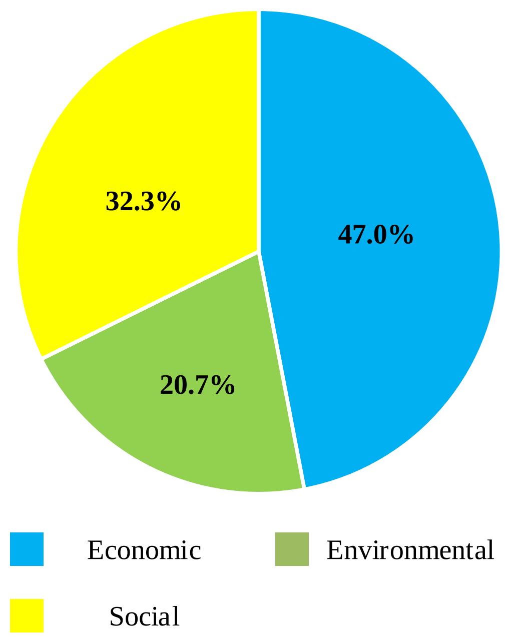

Figure 7-6b: Priority weightages of sustainability indicators in the formation of SI

Figure 7-6: The final priority weightages of respective elements of East Malaysia

In East Malaysia, government (35.48%) has the greatest responsibility to lead the development of the industry in East Malaysia followed by researchers (24.89%), financier (20.29%) and industry players (19.34%). As compared to West Malaysia, researcher plays a more important role here to convince other stakeholders to work together in achieving sustainable integrated biomass supply chain development. It is observed that economic performance (46.99%) is still the major factor that drives the growth of the industry. A high positive social impact (32.33%) is also demanded in West Malaysia to drive the entire industry forward. However, the environmental performance (20.68%) requirement and awareness are relatively lower compared to East Malaysia. This is because the economic and social development is West Malaysia is considered relatively laid back. Therefore, gross profit ranks first with 46.99% followed by processing hub inherent safety (11.21%), transportation safety (11.20%), job opportunity (9.92%), carbon footprint (9.17%), water footprint (6.23%) and land footprint (5.28%). The formulation of SI is displayed as follows.

$$SI = 0.4699S_{GP} + 0.0917S_{CF} + 0.0623S_{WF} + 0.0528S_{LF} + 0.1121S_{IS} + 0.1120S_{TS} + 0.0992S_{JC} \quad (7.13)$$

An illustrative example is presented to demonstrate the assessment and analysis of sustainability performance of a supply chain via the synthesised SIs. Given a 10,000 t of EFB from source *a*, it can be utilised for the generation of DLF at processing hub b_1 or pellet at processing hub b_2. The end-product is then transported to demand *c* as shown in *Figure 7-7*. The individual sustainable indicator of both routes is calculated and shown in *Table 7-7*.

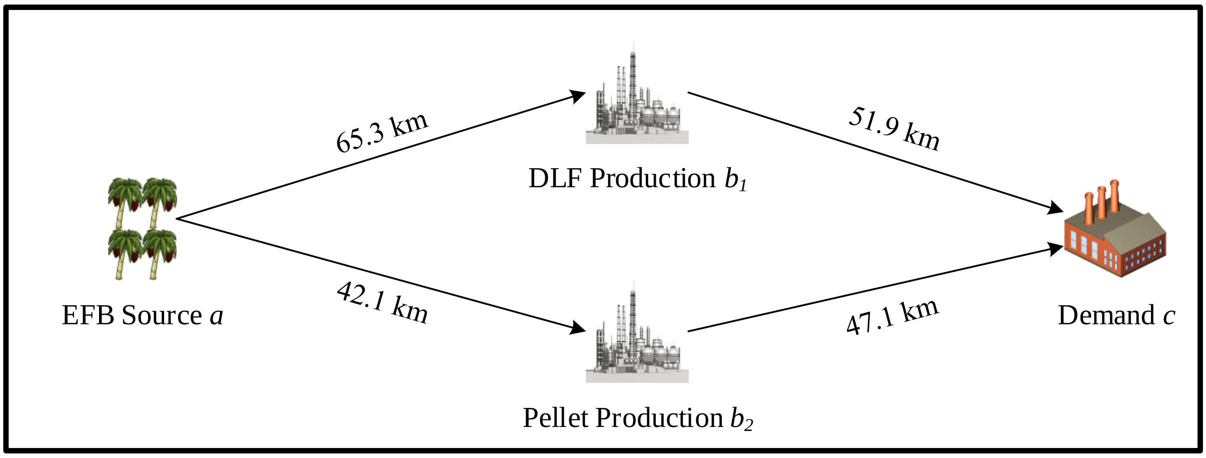

Figure 7-7: Illustrative example

Table 7-7: Individual sustainable indicator scores of two different production routes

Sustainability Indicators	Production of DLF	Production of Pellet
Gross Profit (USD)	145,676	108,404
Carbon Footprint (t CO_2)	76.52	51.88
Water Footprint (m^3 H_20)	571.8	406.3
Land Footprint (m^2 land)	900	810
Inherent Safety Index of Processing Hub	12	11
Transportation Death Risk (10^{-10})	1.336	1.659
Job Creation	7.6	9.9

The sustainability performance of both of the production routes is assessed using the synthesised SIs. The SI score is tabulated in *Table 7-8*. In West Malaysia, DLF production is considered as a more sustainable plan than pellet production. Although pellet production is more environmentally friendly and social favourable, DLF production of having nearly 50% more gross profit outweighs its advantages and contributes more in the SI score. However, it is noted that the difference of the final SI score of these two production routes is very small, which is about 1.9%. This because the SI score is contributed evenly by economic, environmental and social performance in West Malaysia. Despite having DLF production as a more sustainable selection in East Malaysia, the final SI scores of both production choices defer by 7.4%, which is relatively a larger gap as compared to West Malaysia. This is due to the fact that economical factor is more dominant, and it accounts about 50% to the calculation of SI score. The differences in SI scores reflect that every individual has their own perception towards sustainability. It is very much depending on the state of development and people's need. In the urban and developed West Malaysia, sustainability is defined and distributed evenly between the triple bottom line. As for the relatively more rural and remote East Malaysia, economical potential and society needs remain the dominant factor for the sustainable development of integrated biomass supply chain. Rural communities are still lacking in environmental awareness.

Table 7-8: SI score of different production routes in different region

Sustainability Index Score	West Malaysia		East Malaysia	
	DLF	Pellet	DLF	Pellet
Gross Profit	0.1928	0.1265	0.2350	0.1542
Carbon Footprint	0.0642	0.0947	0.0458	0.0676
Water Footprint	0.0390	0.0548	0.0312	0.0439
Land Footprint	0.0256	0.0284	0.0264	0.0293
Inherent Safety Index of Processing Hub	0.0788	0.0860	0.0560	0.0611
Transportation Death Risk	0.0678	0.0546	0.0695	0.0560
Job Creation	0.0315	0.0451	0.0346	0.0496
Total SI	0.4995	0.4901	0.4985	0.4617

7.5 Conclusion

With rising global demand for sustainable development, the implementation of sustainability practices in integrated biomass supply chain is crucial to the growth of biorefinery industry. This chapter proposes a novel methodology to develop a sustainability assessment framework with FANP. The presented model enables the incorporation of human preferences on sustainability indicators to derive a sustainability index. By taking into consideration human factors for sustainability development, the model provides a more feasible solution to aid industry stakeholders to access and analyse the sustainability performance of an integrated biomass supply chain. Furthermore, it also helps to enhance the decision-making process on selecting technology and processes that not only maximise economic performance, but also preserve and conserve the environment while improving social well-being. It should be noted that the priority weights derived with FANP can be vary depending on the problem structures based on the nature and main objective of the projects. As demonstrated in the case study, the SIs synthesised may also differ according to different groups of target respondents even with identity problem structure and objective. This is caused by the difference in level of understanding and demand of the stakeholders towards sustainability of integrated biomass supply chain.

As sustainable indicators often conflict between each other, a framework is then proposed in the next chapter to incorporate the synthesised SI for the optimisation of integrated biomass supply chain. The detailed calculation and trade-off between these indicators will also be discussed.

CHAPTER 8

FUZZY ANALYTICAL PROCESS NETWORK-AIDED (FANP) MULTIPLE OBJECTIVES OPTIMISATION APPROACH FOR INTEGRATED BIOMASS SUPPLY CHAIN

8.1 Introduction

Sustainable supply chain management (SSCM) has always been focusing on the management of material flows along the supply chain while targeting to optimise the triple bottom line (economic, environment and social) of sustainable development. As opposed to single-objective optimisation (SOO), SCCM is a multi-objective optimisation (MOO) problem because the objectives of each of the sustainability factors often appear to be conflicting and contradicting. For instance, improving the safety and environmental performance of the supply chain could cause a drop in its economic performance (Čuček et al., 2012c). Therefore, it is challenging to find a single solution that simultaneously satisfies all objectives as optimising an objective often requires the trade-off and compromise of other objectives.

The most commonly used approach for MOO problem is the weighted sum method. In this model, multiple objective functions are transformed into a single-objective function by assigning a priority weightage to each objective. The problem is then solved by optimising the weighted sum of all the objectives. The simplicity in application makes this approach attractive as it requires minimum labour and computational effort for problem solving. However, it requires the prior knowledge of decision makers while defining the weightage of each objective. In other words, inconsistencies in any specified weight will lead to biased results. Besides, the weighted sum model requires multiple objective functions to be quantified with the same scale. Otherwise, the optimised result from the model may not represent an accurate trade-off between targeted objectives.

On the other hand, fuzzy optimisation model has been widely utilised to solve MOO problems. Multiple contradicting objectives are integrated into a single continuous interdependence variable λ known as the degree of satisfaction (Bellman and Zadeh, 1970). This is achieved by normalising each solution of an objective between 0 and 1 (0 being the worst while 1 being the best). With λ representing the interaction between several considered objectives, it is maximised subject to pre-set upper and lower bounds in order to obtain the highest satisfaction of each objective (Tan et al., 2011). Hence, only the partial satisfaction of the objectives may be achieved, resulting a compromise solution among all considered objectives. This can be understood as max-min aggregation rule, where the λ of the least satisfied objective is maximised. (Zimmermann, 1978). The drawback of this method is that all objectives are given equal priority and the preferences of the decision makers are not captured.

Therefore, this chapter proposes a novel FANP-aided multi-objective optimisation approach for the synthesis of an integrated sustainable biomass supply chain. To illustrate the proposed framework, the previous Johor case study is resimulated.

8.2 FANP-Aided Multiple Objectives Optimisation

To overcome the limitations of the conventional MOO approaches, this section presents a FANP-aided multiple objectives optimisation framework to solve the SCCM problem. The concept of the introduced framework is displayed in *Figure 8-1*.

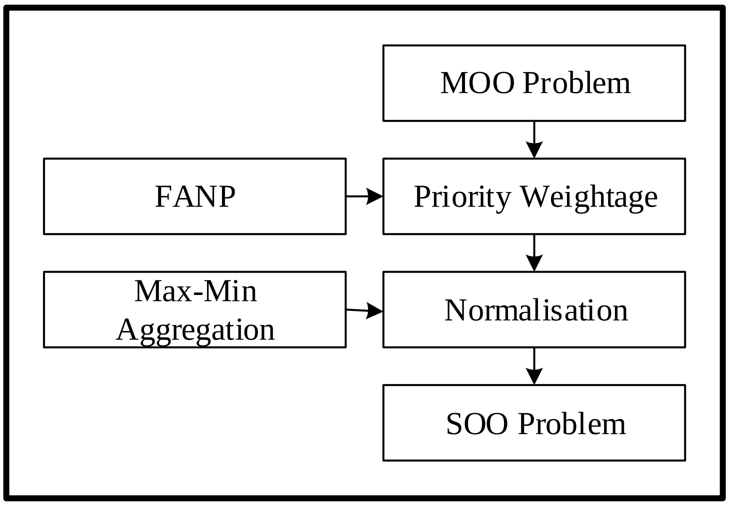

Figure 8-1: Concept of FANP-aided multiple objectives optimisation

In this framework, FANP is adopted to assign priority weightages of each sustainability indicators. As discussed in Chapter 7, these weightages are derived from pairwise comparisons conducted by a group of decision makers among the objectives considered thus capturing the preferences of decision makers into the model. At the same time, it reduces the decision makers' tendencies of bias while weighting objectives. Furthermore, the fuzziness introduced in FANP can minimise the inconsistencies and uncertainties in the pairwise comparison judgement.

To ensure the considered objectives are comparable and their trade-offs are of the same scale, max-min aggregation is adapted from fuzzy optimisation to normalise the original values. For sustainable indicators that need to be maximised, the normalisation is defined as:

$$S_y^{Nor} = \frac{S_y - \mathrm{S}_y^{\mathrm{L}}}{\mathrm{S}_y^{\mathrm{U}} - \mathrm{S}_y^{\mathrm{L}}} \qquad \forall y \in Y \qquad (8.1)$$

where S_y is the original value of sustainability indicators y; $\mathrm{S}_y^{\mathrm{U}}$ and $\mathrm{S}_y^{\mathrm{L}}$ are predefined upper and lower limit; S_y^{Nor} is the normalised value which is bounded between 0 and 1. As S_y approaches the upper bound, S_y^{Nor} becomes 1 (most satisfied). Otherwise, S_y^{Nor} approaches 0 (least satisfied) when S_y is close to lower bound. This can be observed in *Figure 8-2*.

For minimisation, it is completely the opposite. When S_y approaches lower bound, it will lead to full satisfaction whereas approaching upper bound will lead to least satisfaction. The normalisation of objectives in this case can be defined as:

$$S_y^{Nor} = \frac{\mathrm{S}_y^{\mathrm{U}} - S_y}{\mathrm{S}_y^{\mathrm{U}} - \mathrm{S}_y^{\mathrm{L}}} \qquad \forall y \in Y \qquad (8.2)$$

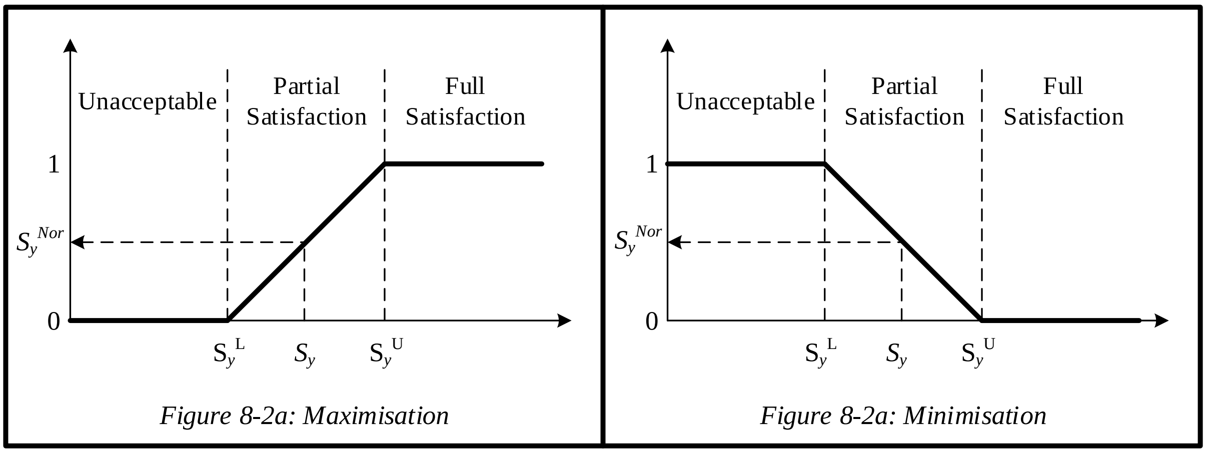

Figure 8-2: Max-min aggregation

The objective function of SCCM has been transform into SOO and it can be defined as:

$$Maximise\ SI = \sum_{y=1}^{Y} w_y S_y^{Nor} \qquad \forall y \in Y \qquad (8.3)$$

where SI is the sustainability index score and w_y is the priority weightage assigned for each objective with FANP.

SSCM ensures integrated biomass supply chain remain competitive in economic operation, environmental and social performance. The sustainability in economic, environment and social can be measured and calculated through various sustainability indicators. A detailed discussion on each of these sustainability indicators will be presented in the next chapter.

8.3 Sustainability Indicators

As mentioned in Chapter 2, integrated biomass supply chain is defined as the activities associated with biomass delivery, biomass processing and product distribution. These activities will generate economic value, leaving an impact on the environment and society at the same time. To ensure sustainable development of the industry, it is important to consider three of these factors while designing an integrated biomass supply chain. There are various existing indicators which can quantify the sustainability of integrated biomass supply chain in terms of economic performance, environmental friendliness and social well-being.

In the FANP framework as discussed in Chapter 7, a focus group has been conducted to identify the appropriate sustainability indicators in the context of integrated biomass supply chain. For the economic indicator, gross profit is selected as it can reflect the profitability and financial successfulness of an integrated biomass supply chain in a direct manner. Within the scope of integrated biomass supply chain, gross profit is commonly defined as the profit made after deducting the costs of production and logistics of the products.

Since carbon dioxide is produced and water is consumed along the supply chain, water and carbon footprints are adopted to measure the environmental impact of the system. Besides, the total land area utilised throughout the process is measured by land footprint. The definition of respective footprints and how they are adapted in the system are stated in *Table 8-1*. As observed from the table, footprints generated during crop cultivation is not considered in the sustainability evaluation of integrated biomass supply chain. This is because all biomass is assumed as crop residues or process wastes. These footprints are generated primarily due to the demand of food but not cultivation of biomass.

Table 8-1: Definition and adoption of environmental footprints

Footprint	Definition	Adaptation in Integrated Biomass Supply Chain
Carbon	It is defined as the total amount of CO_2 emitted over the life cycle of product (POST, 2006). It can also be stated as the land area required for afforestation to compensate the CO_2 produced along the process.	Measurement of total CO_2 produced from the processing of biomass, transportation of biomass and power consumption along the biomass supply chain.
Water	It is divided into 3 components (Gerben-Leenes et al., 2012) as: • Green water footprint: Consumption of rainwater for the cultivation of crops • Blue water footprint: Consumption of surface or ground water for the production • Grey water footprint: Consumption of fresh water for the assimilation of pollutants It can also be defined as the total amount of water utilised in the life cycle of a product (Hoekstra, 2003).	Summation of the following water footprint: • Process-based water footprint: Water consumption of biomass processing • Fuel-based water footprint: Water consumption of transportation • Power-based water footprint: Water consumption of power generation
Land	It is the total land area that is required throughout the process (Giljum et al., 2013).	Total land required for the settlement of processing hub.

Social sustainability has received limited attention as compared to economic performance and environmental impact. This is due to the fact that the conceptual clarification for social sustainability is yet to be firm and solid (Gopal and Thakkar, 2016). Safety is one of the commonly used standards to measure the social sustainability of integrated biomass supply chain (Mani et al., 2014). It is noted that the safety of workers has a positive impact on the social sustainability of an organisation (Saunders et al., 2015). Hence, inherent safety index

(ISI) is utilised to quantify the safety performance of the processing plant. ISI is the extension of Prototype inherent safety index (PIIS), one of the pioneering safety indices (Edward and Lawrence, 1993). It is used to evaluate the safety of process routes based on inventory, flammability, explosiveness and toxicity. The extended PIS covers a wider scope which includes corrosion, side reactions and outside battery limit (Heikkilä, 1999). As for transportation safety, the risk of death caused by road accident is measured. As society and community will be benefited directly from job opportunities created within the supply chain, job creation is also selected as one of the sustainability indicators.

8.4 Problem Statement

The multiple objectives optimisation (MOO) problem described in this chapter aims to determine the optimal technology selection and logistic network for an integrated biomass supply chain with maximum economic and social benefits, while keeping environmental impact at minimal. The synthesis problem then can be formally stated as follows: given a set of biomass types $i \in I$ supplied from a set of sources $a \in A$ is delivered to a set of processing hubs $b \in B$. Then, it is converted into a set of intermediates $k \in K$ and a set of products $m \in M$ via a set of technologies $j \in J$ and $l \in L$. Finally, products $m \in M$ will be delivered to a set of demands $c \in C$. Besides, energy (i.e. electricity and steam) $e \in E$ can be produced from biomass type *i* and intermediate *k* via technology *j* and *l* to sustain the process or to be exported. Throughout the entire supply chain, a set of environmental impacts $n \in N$ and a set of social impacts $o \in O$ are released. The generic representation of the problem is shown in *Figure 8-3*. Based on the superstructure, a fuzzy analytical network process-aided (FANP) multiple objectives optimisation (MOO) approach is presented to address integrated biomass supply chain problem. The following section further explains the development of this methodology.

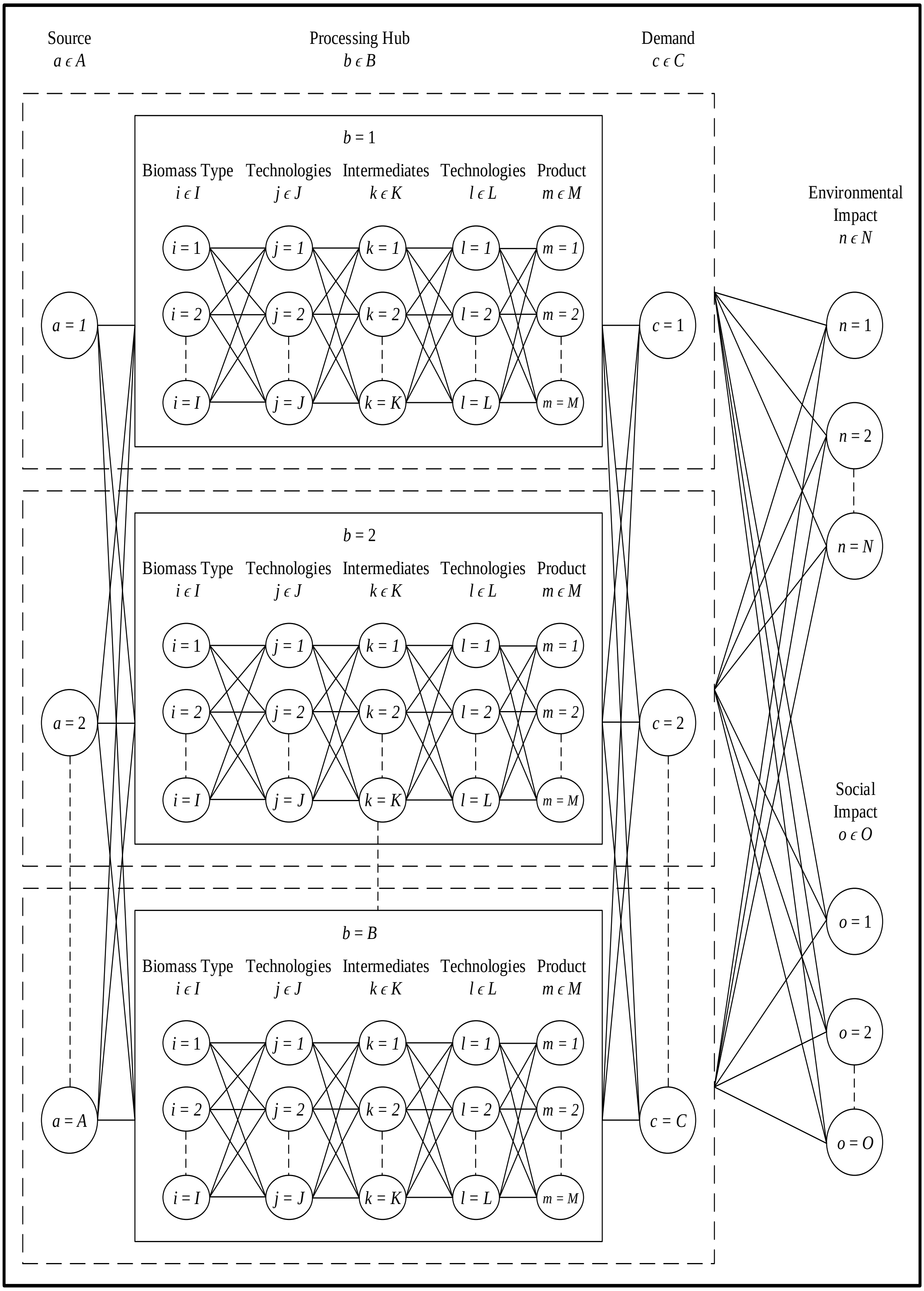

Figure 8-3: Superstructure of the MOO problem

8.5 Methodology

The fuzzy analytical network process-aided (FANP) multiple objectives optimisation approach introduced in this chapter aims to generate a "compromise solution" among the optimisation objectives. *Figure 8-4* shows the comprehensive methodology of the proposed FANP-aided multiple objectives optimisation approach. The framework consists of three important steps which are data collection, FANP model and mathematical formulation. Information reviewed and the priority weightage obtained from FANP model will serve as an input to the mathematical model. These two steps have been demonstrated in Chapter 4 and Chapter 7 respectively. Therefore, the main focus of this chapter is to illustrate the model formulation, in which the multi-objectives optimisation problem is transformed into a single-objective optimisation problem via max-min aggregation with the input from data collection and FANP framework.

The mathematical model formulation starts from the superstructure construction of processing network and logistic network. The material flow along the supply chain is then formulated according to these drawn superstructures. They can be adopted directly from MBC approach proposed in Chapter 4. Based on the mass balance, multiple objective functions are developed. In this work, the objective functions are gross profit, carbon footprint, water footprint, land footprint, inherent safety index (ISI), transportation death risk and job opportunities as discussed in the previous section. As these objectives are measured and calculated in a different units and scales, they are normalised to the same scale to ensure the integrity and consistency between the trade-offs. This is done via max-min aggregation. Last but not least, priority weightage derived from the FANP framework is assigned to each of the objective function, forming a single objective which is the sustainability of the supply chain.

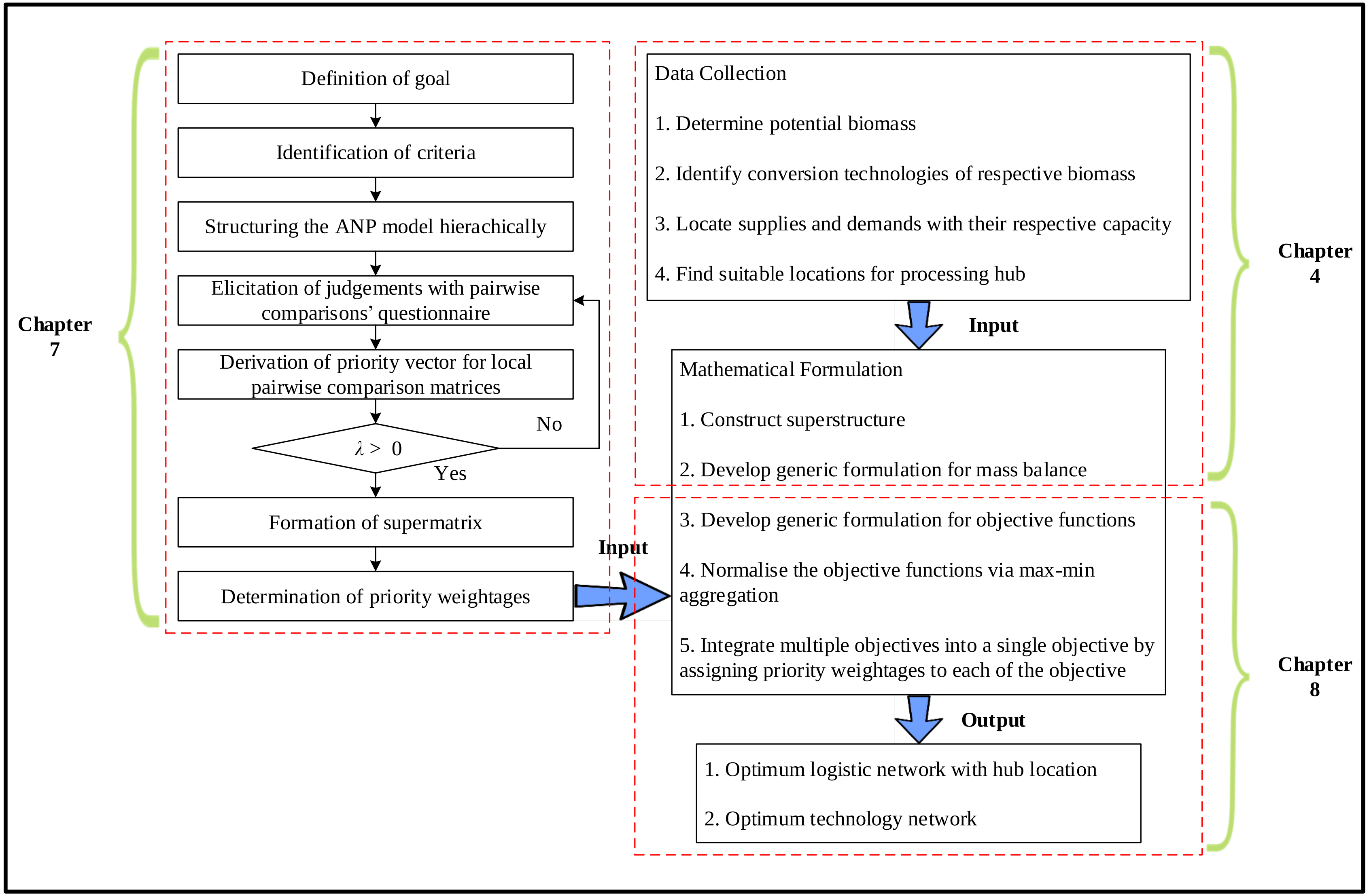

Figure 8-4: FANP-aided multiple objectives optimisation framework

The model is then solved to determine the optimum logistic network and biorefinery structure in terms of sustainability. In the following section, the mathematical equations formulated in this optimisation model are comprehensibly defined and explained methodically to address a multi-objectives integrated biomass supply chain synthesis problem.

8.6 Mathematical Formulation

This model is capable of solving integrated biomass supply chain synthesis problem based on multiple conflicting and contradicting objectives, achieving a sustainable development in the industry. Based on Figure 8-4, Sections 8.6.1-8.6.5 present a detailed formulation of the proposed multi-objectives optimisation model.

8.6.1 Material Balance

The material balance is the foundation of the model and it is formulated sequentially from the biomass allocation to technology selection and product distribution. As multiple biomass types and processing technologies are considered, Equations 4.1 – 4.16 are adapted from Chapter 4 to present the material flow of this work.

8.6.2 Economic Performance

Similar to previous work, gross profit is used to evaluate the economic potential of integrated biomass supply chain in this model. The gross profit S_{GP} is reformulated as the difference between the revenue of the supply chain C^{RE} and cost incurred by the activities throughout the supply chain C^{IN}.

$$S_{GP} = C^{RE} - C^{IN} \tag{8.4}$$

$$C^{RE} = AC^{RE} \tag{8.5}$$

$$C^{IN} = AC^{PR} + AC^{TR} + AC^{IN} \tag{8.6}$$

where AC^{RE}, AC^{PR}, AC^{TR} and AC^{IN} stand for annualised revenue, production cost, transportation cost and investment cost respectively.

8.6.3 Environmental Performance

Activities along the supply chain leave an impact on the environment, which includes production of carbon dioxide as well as water and land consumption. To ensure the environmental sustainability of the industry, carbon, water and land footprints are measured and optimised. The calculation of respective footprints is presented in the following subsections.

8.6.3.1 Carbon Footprint

Carbon dioxide is produced from the processing of biomass, fuel consumption during transportation and power consumption by the processing hub. The calculation of carbon footprint can then be formulated as follows:

$$S_{CF} = S_{CF}^{Process} + S_{CF}^{Fuel} + S_{CF}^{Power} \tag{8.7}$$

where S_{CF} stands for total carbon footprint of the supply chain; $S_{CF}^{Process}$, S_{CF}^{Fuel} and S_{CF}^{Power} represent the CO_2 emitted from the process, fuel consumption and power generation respectively. $S_{CF}^{Process}$ is defined as the total CO_2 emitted during the process of m production with emission factors of EF_m.

$$S_{CF}^{Process} = \sum_{m \in M} \sum_{b \in B} F_m^b \, \mathrm{EF}_m \tag{8.8}$$

For S_{CF}^{Fuel}, it formulated as the total CO_2 emitted by trucks with emission factor of $\mathrm{EF_{fuel}}$.

$$S_{CF}^{Fuel} = \sum_{a \in A} \sum_{b \in B} F_{a,b} \mathrm{D}_{a,b} \, \mathrm{EF_{fuel}} + \sum_{b \in B} \sum_{c \in C} F_{b,c} \mathrm{D}_{b,c} \mathrm{EF_{fuel}} \tag{8.9}$$

Lastly, S_{CF}^{Power} is the total CO_2 emitted from the production of power (with emission factor of $\mathrm{EF_{power}}$) consumed by the processing hub.

$$S_{CF}^{Power} = \sum_{b \in B} F_{e,IM}^{b} \, \mathrm{EF_{power}} \tag{8.10}$$

8.6.3.2 Water Footprint

To minimise the water wastage within the supply chain, water footprint is calculated to measure the total amount of water consumed throughout the activities. The total water input of the supply chain is equivalent to the total water consumed by production of bioproducts, fuel and power as stated below:

$$S_{WF} = S_{WF}^{Process} + S_{WF}^{Fuel} + S_{WF}^{Power} \tag{8.11}$$

where S_{WF} is the total water footprint of the system; $S_{WF}^{Process}$, S_{WF}^{Fuel} and S_{WF}^{Power} refer to process-based, fuel-based and power-based water consumption respectively. The formulation of these water footprints is shown as follows.

$$S_{WF}^{Process} = \sum_{m \in M} \sum_{b \in B} F_{m}^{b} \, WR_{m} \tag{8.12}$$

$$S_{WF}^{Fuel} = \sum_{a \in A} \sum_{b \in B} F_{a,b} \mathrm{D}_{a,b} \, \mathrm{WR_{fuel}} + \sum_{b \in B} \sum_{c \in C} F_{b,c} \mathrm{D}_{b,c} \, \mathrm{WR_{fuel}} \tag{8.13}$$

$$S_{WF}^{Power} = \sum_{b \in B} F_{e,IM}^{b} \, \mathrm{WR_{power}} \tag{8.14}$$

where $\mathrm{WR_{fuel}}$ indicates the water required for delivery of biomass and bioproducts; WR_{m} and $\mathrm{WR_{power}}$ denote the water needed for production of *m* and power.

8.6.3.3 Land Footprint

Land footprint is a consumption-based environmental indicator that measures the land requirement in creating a final product. In integrated biomass supply chain, land consumption S_{LF} is affected by the number of hubs and the capacity of production. Hence, it is formulated as the sum of both of these components.

$$S_{LF} = S_{LF}^{Hub} + S_{LF}^{Capacity} \tag{8.15}$$

where $S_{LF}^{Process}$ and S_{LF}^{Hub} refer to the land required for different biomass processing technologies and hub construction consequently. The formulation of these elements is described as follows:

$$S_{LF}^{Hub} = \sum_{b \in B} \beta_b \, \mathrm{LR_{hub}} \tag{8.16}$$

$$S_{LF}^{Capcity} = \sum_{b \in B} \sum_{m \in M} F_m^b \, \mathrm{LR_{capcity}} \tag{8.17}$$

where $\mathrm{LR_{hub}}$ and $\mathrm{LR_{capacity}}$ represent the fixed area needed for construction of a hub and proportional land required for a hub with capacity of 1 tonne of product.

8.6.4 Social Performance

In developing countries, social sustainability has become an essential aspect to guarantee long-term development and survivability of an industry (Klemeš et al., 2012). Hence, monitoring the safety of supply chain activities is the social responsibility of stakeholders in the industry. In this work, safety of processing hub is indicated by inherent safety index (ISI), whereas transportation safety is to minimise the risk of death caused by road accidents. For society welfare, job employment is also predicted. Refer to the following subsections for the formulation of these social indicators.

8.6.4.1 Safety of Processing Hub

As one of the social indicators, the safety of the processing hub is evaluated via ISI (Hurme and Heikkilä, 1998). The ISI of the processing plant S_{ISI} is the summation of the ISI of processes l ($\mathrm{S}_{\mathrm{ISI}}^{l}$).

$$S_{ISI} = \sum_{l \in L} \beta_l \, \mathrm{S}_{\mathrm{ISI}}^{l} \qquad (8.18)$$

$$\beta_l \mathrm{M} \geq \sum_{b \in B} \sum_{k \in K} F_{k,l}^{b} \qquad \forall l \in L \qquad (8.19)$$

β_l is a binary variable that denotes the selection of process l while M refers to a sufficiently large positive constant. When $F_{k,l}^{b}$ is non-zero, β_l will be forced to "1" to fulfil the inequalities. It is worth to note that when $F_{k,l}^{b}$ is zero, β_l can be either "0" or "1". However, this will not be an issue as the objective is to minimise ISI. Thus, β_l will be forced to "0" to reduce total ISI.

The $\mathrm{S}_{\mathrm{ISI}}^{l}$ contains two elements, which are the ISI of chemical $\mathrm{S}_{\mathrm{ISI\_chemical}}^{l}$ and ISI of process specification $\mathrm{S}_{\mathrm{ISI\_process}}^{l}$. The equation can be formulated as below:

$$\mathrm{S}_{\mathrm{ISI}}^{l} = \mathrm{S}_{\mathrm{ISI\_chemical}}^{l} + \mathrm{S}_{\mathrm{ISI\_process}}^{l} \qquad \forall l \in L \qquad (8.20)$$

$\mathrm{S}_{\mathrm{ISI\_chemical}}^{l}$ is based on the heat of main reaction $\mathrm{S}_{\mathrm{ISI\_HRM}}^{l}$, heat of side reaction $\mathrm{S}_{\mathrm{ISI\_HRS}}^{l}$, chemical interaction $\mathrm{S}_{\mathrm{ISI\_CI}}^{l}$, flammability $\mathrm{S}_{\mathrm{ISI\_FL}}^{l}$, explosiveness $\mathrm{S}_{\mathrm{ISI\_EX}}^{l}$, toxic exposure $\mathrm{S}_{\mathrm{ISI\_TE}}^{l}$ and chemical corrosiveness $\mathrm{S}_{\mathrm{ISI\_CC}}^{l}$.

$$\begin{aligned}\mathrm{S}_{\mathrm{ISI\_chemical}}^{l} = {} & \mathrm{S}_{\mathrm{ISI\_HRM}}^{l} + \mathrm{S}_{\mathrm{ISI\_HRS}}^{l} + \mathrm{S}_{\mathrm{ISI\_CI}}^{l} + \mathrm{S}_{\mathrm{ISI\_FL}}^{l} \\ & + \mathrm{S}_{\mathrm{ISI\_EX}}^{l} + \mathrm{S}_{\mathrm{ISI\_TE}}^{l} + \mathrm{S}_{\mathrm{ISI\_CC}}^{l}\end{aligned} \qquad \forall l \in L \qquad (8.21)$$

As for $\mathrm{S}^{l}_{\mathrm{ISI\_process}}$, it contains process inventory $\mathrm{S}^{l}_{\mathrm{ISI\_IN}}$, process temperature $\mathrm{S}^{l}_{\mathrm{ISI\_PT}}$, process pressure $\mathrm{S}^{l}_{\mathrm{ISI\_PP}}$, equipment safety $\mathrm{S}^{l}_{\mathrm{ISI\_ES}}$ and process structure safety $\mathrm{S}^{l}_{\mathrm{ISI\_PS}}$. All these values can be predetermined, and they are calculated based on worst-case scenario (least safe). Note that an inherently safer integrated biomass supply chain owns a low value of ISI.

$$\mathrm{S}^{l}_{\mathrm{ISI\_process}} = \mathrm{S}^{l}_{\mathrm{ISI\_IN}} + \mathrm{S}^{l}_{\mathrm{ISI\_PT}} + \mathrm{S}^{l}_{\mathrm{ISI\_PP}} + \mathrm{S}^{l}_{\mathrm{ISI\_ES}} + \mathrm{S}^{l}_{\mathrm{ISI\_PS}} \qquad \forall l \in L \qquad (8.22)$$

8.6.4.2 Safety of Transportation

Road accident is a major threat to transportation safety. Although it can result in different consequences, the worst-case scenario is assumed. Hence, the social impact arose from road accident only takes the risk of death into account. The risk varies from road to road so the total death risk S_{DR} is calculated as the sum of the risk from source a to hub b ($\mathrm{S}^{a,b}_{\mathrm{DR}}$) and the death risk from hub b to demand c ($\mathrm{S}^{b,c}_{\mathrm{DR}}$).

$$S_{DR} = \sum_{a \in A} \beta_{a,b}\, \mathrm{S}^{a,b}_{\mathrm{DR}} + \sum_{c \in C} \beta_{b,c}\, \mathrm{S}^{b,c}_{\mathrm{DR}} \qquad \forall b \in B \qquad (8.23)$$

$$\beta_{a,b}\mathrm{M} \geq F_{a,b} \qquad \forall a \in A, \forall b \in B \qquad (8.24)$$

$$\beta_{b,c}\mathrm{M} \geq F_{b,c} \qquad \forall b \in B, \forall \mathrm{c} \in C \qquad (8.25)$$

Again, a sufficiently large positive constant M method is inserted into the inequalities, whereas $\beta_{a,b}$ and $\beta_{b,c}$ are binary variables that denote the selection of route.

8.6.4.3 Job Opportunities

As welfare to society, integrated biomass supply chain creates job employments. The social impact in terms of job opportunities created by the entire value chain S_{JO} is estimated based on the job vacancies from the processing unit $S_{JO}^{Process}$ and logistic operation $S_{JO}^{Transport}$.

$$S_{JO} = S_{JO}^{Process} + S_{JO}^{Transport} \tag{8.26}$$

$$S_{JO}^{Process} = \sum_{m \in M} \sum_{b \in B} \left(\mathrm{S}_{\mathrm{JO}}^{m} F_{m}^{b} \right) \tag{8.27}$$

$$S_{JO}^{Transport} = \mathrm{S}_{\mathrm{JO}}^{Truck} N_{truck} \tag{8.28}$$

where $\mathrm{S}_{\mathrm{JO}}^{m}$ is the workers needed the production of product m; $\mathrm{S}_{\mathrm{JO}}^{Truck}$ is the number of truck drivers required for a given number of truck N_{truck}.

8.6.5 Objective Function

Sustainability indicators are often contradicting each other. In this model, gross profit and job opportunities opt for maximisation whereas environmental footprints, ISI and transportation death risk require minimisation. To address these conflicting objectives, FANP-aided multi-objective optimisation approach is introduced to transform the MOO problem into a SOO problem. First, the objective functions are normalised to the same scale via max-min aggregation to ensure trade-offs between considered objectives are equal and comparable. The normalised value ranges from 0 to 1, with 1 being most satisfied and 0 being least satisfied. The formulation of the normalisation is adopted from Equations 8.1 and 8.2 and stated as follows:

$$S_{GP}^{Nor} = \frac{S_{GP} - \mathrm{S}_{\mathrm{GP}}^{\mathrm{L}}}{\mathrm{S}_{\mathrm{GP}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{GP}}^{\mathrm{L}}} \tag{8.29}$$

$$S_{CF}^{Nor} = \frac{\mathrm{S}_{\mathrm{CF}}^{\mathrm{U}} - S_{CF}}{\mathrm{S}_{\mathrm{CF}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{CF}}^{\mathrm{L}}} \tag{8.30}$$

$$S_{LF}^{Nor} = \frac{\mathrm{S}_{\mathrm{LF}}^{\mathrm{U}} - S_{LF}}{\mathrm{S}_{\mathrm{LF}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{LF}}^{\mathrm{L}}} \tag{8.31}$$

$$S_{WF}^{Nor} = \frac{\mathrm{S}_{\mathrm{WF}}^{\mathrm{U}} - S_{WF}}{\mathrm{S}_{\mathrm{WF}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{WF}}^{\mathrm{L}}} \tag{8.32}$$

$$S_{ISI}^{Nor} = \frac{\mathrm{S}_{\mathrm{ISI}}^{\mathrm{U}} - S_{ISI}}{\mathrm{S}_{\mathrm{ISI}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{ISI}}^{\mathrm{L}}} \tag{8.33}$$

$$S_{DR}^{Nor} = \frac{\mathrm{S}_{\mathrm{DR}}^{\mathrm{U}} - S_{DR}}{\mathrm{S}_{\mathrm{DR}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{DR}}^{\mathrm{L}}} \tag{8.34}$$

$$S_{JO}^{Nor} = \frac{S_{JO} - \mathrm{S}_{\mathrm{JO}}^{\mathrm{L}}}{\mathrm{S}_{\mathrm{JO}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{JO}}^{\mathrm{L}}} \tag{8.35}$$

where the upper and lower boundaries of these objectives are the maximum and minimum values predetermined based on the optimisation of a single objective at one time.

Together with the priority weightage derived from the FANP framework, these objectives are integrated into a single objective, which is the sustainability index SI. SI measures the sustainability performance of the supply chain and is formulated as follows:

$$SI = w_{GP}S_{GP}^{nor} + w_{CF}S_{CF}^{nor} + w_{WF}S_{WF}^{nor} + w_{LP}S_{LP}^{nor} + w_{ISI}S_{ISI}^{nor} + w_{DR}S_{DR}^{nor} + w_{JO}S_{Jo}^{nor} \tag{8.36}$$

Therefore, an optimum integrated biomass supply chain can be obtained by maximising the SI.

$$Maximise\ SI \tag{8.37}$$

The FANP-aided multi-objectives optimisation approach is then demonstrated on a case study in the following section.

8.7 Case Study

As a demonstration of the framework, the Johor case study is revisited. With the same setting, the case study is resimulated with a different objective, which is to design a supply chain system with maximum sustainability performance. Based on the superstructure in *Figure*

4-4, the material flow along the supply chain is formulated via Equations 4.1 – 4.16 with the location and mass flowrate data collected in Chapter 4. To determine the economic performance of the supply chain, Equations 4.18 – 4.22 and 8.4 – 8.6 are constructed. The economic data required for gross profit calculation can also be obtained from Chapter 4.

For the calculation of carbon and water footprint of each process, the emission factor and water demand are provided in *Table 8-2*. As the estimation only accounts for CO_2 production and water consumption by the process, the value of emission factor and water demand of some of the processes are 0, especially physical conversion. As for the carbon and water footprint caused by the power consumption of these processes, they are considered in the computation of power-based carbon and water footprint.

Table 8-2: Emission factor and water demand of respective processes

Process	**Emission Factor**	**Water Demand**
	t CO_2/t product	**m^3/t product**
DLF Production	0.000	0.000
Energy Pack Production	0.000	0.000
Pellet Production	0.000	0.000
Slow Pyrolysis	0.041[a]	0.023[g]
Fast Pyrolysis	0.046[b]	0.023[g]
Acid Fermentation	0.113[c]	0.149[h]
Alkaline Fermentation	0.121[c]	0.151[h]
Hot Water Fermentation	0.115[c]	0.169[h]
Steam Explosion Fermentation	0.087[c]	0.115[h]
Citric Acid Production	0.030[d]	0.021[i]
Formic Acid Production	0.035[d]	0.026[i]

Table 8-2 (con't): Emission factor and water demand of respective processes

Process	Emission Factor	Water Demand
	kg CO_2/kWh power	**m^3/kWh power**
Gas Turbine	0.097[e]	0.022[e]
Steam Turbine	0.159[f]	0.017[j]

[a]NCPC (2014); [b]Steele et al. (2012); [c]Wang et al. (2013); [d]Prado et al. (2005); [e]EPA (1998); [f]Akagi et al. (2011); [g]Hsu (2011); [h]Kumar and Murthy (2011); [i]James and Currie (1917); [j]Pikoń (2012)

In this case study, power from the national grid is imported to sustain activities within the processing hub. The power is generated from a mixture of different power plants. The power generation, emission factors and water demand of these power plants are tabulated in *Table 8-3*. The emission factor $\mathrm{EF_{power}}$ and water requirement $\mathrm{WR_{power}}$ of the power consumption can be estimated as follows:

$$\mathrm{EF_{power}} = \frac{\sum_{\mathrm{PP}} \mathrm{PG_{pp}EF_{pp}}}{\sum_{\mathrm{pp}} \mathrm{PG_{pp}}} \tag{8.38}$$

$$\mathrm{WR_{power}} = \frac{\sum_{\mathrm{PP}} \mathrm{PG_{pp}WR_{pp}}}{\sum_{\mathrm{pp}} \mathrm{PG_{pp}}} \tag{8.39}$$

where $\mathrm{PG_{pp}}$, $\mathrm{EF_{pp}}$ and $\mathrm{WR_{pp}}$ refer to power generation of each power plant, emission factor for power generation and water requirement during power generation.

The water requirement for fuel consumption is defined as the product of crude oil production water footprint $\mathrm{WR_{COP}}$ and energy needed for truck operation $\mathrm{WR_{truck}}$, stated as:

$$\mathrm{WR_{fuel}} = \mathrm{WR_{COP}WR_{truck}} \tag{8.40}$$

By solving Equations 8.38 – 8.40, the data required for the estimation of respective footprints for power and fuel consumption of supply chain is summarised in *Table 8-4*.

Table 8-3: Data of respective power plants

Power Plant	**Power Generation**[1] **(MW)**	**Emission Factor**[2] **(kg CO_2/kWh)**	**Water Demand**[3] **(m^3/kWh)**
Combined Cycle	317	0.702	0.684
Coal-Fired	480	1.180	0.688
Hydro	96	0.041	20.016
Gas Turbine	271	1.222	0.684
Diesoline	114	0.218	1.224

[1]SEB (2010); [2]Shekarchian et al. (2008); [3]Okadera et al. (2014)

Table 8-4: Data calculated for footprints estimation

	Power Consumption	**Fuel Consumption**
Emission Factor	0.8990 kg CO2/kWh	0.092 kg CO2/km t product[1]
Water Demand	0.0022 m3/kWh	0.024 m3/km t product

[1]European Environment Agency (n.d.)

As discussed previously, the land footprint of integrated biomass supply chain considers only the land needed for hub construction. Land required for crop cultivation is not accounted because biomass utilised in this case study is considered as waste. The crop land is solely intended for the production of food instead of biomass. The land footprint of hub construction consists of two components which are fixed area for hub construction and proportional area for hub capacity as denoted by Equation 8.15. In this work, they are assumed as 20,000 m^2/hub and 0.019 m^2/t product respectively.

Equation 8.20 is solved to identify the ISI of each process. The ISI score of for the elements considered within the scope as shown in Equations 8.21 and 8.22 is determined according to the ISI user manual introduced by Hurme and Heikkilä (1998). The result is displayed in Table *8-5*.

Table 8-5: ISI scores of processes

Process	**ISI**
DLF Production	12
Energy Pack Production	13
Pellet Production	10
Slow Pyrolysis	30
Fast Pyrolysis	31
Acid Fermentation	22
Alkaline Fermentation	22
Hot Water Fermentation	24
Steam Explosion Fermentation	26
Citric Acid Production	25
Formic Acid Production	27
Gas Turbine	30
Steam Turbine	35

According to the statistic provided by the Ministry of Transport (MOT) Malaysia in 2017, the average death risk caused by road accident in the state of Johor is provided as 0.049 death/km annually. The data is provided by MOT is limited, which is only presented at the national and state level. Therefore, it is assumed that the death risk of all the routes within the state is identity to the average transportation risk of death of the state.

Apart from significant economic growth, the commercialisation of integrated biomass supply chain will result in an increment of job opportunities. The quantity of jobs offered by the different processes in the processing hub is compiled in *Table 8-6*. As for logistic network, the jobs created can be estimated through Equation 8.28. The number of trucks required is estimated as follows:

$$N_{truck} = \frac{\sum_{b \in B} \sum_{m \in M} F_m^b}{\mathrm{CA_{truck}} \mathrm{N_{trip}}} \tag{8.41}$$

where $\mathrm{CA_{truck}}$ and $\mathrm{N_{trip}}$ are the capacity and number of trips travelled of the truck. The job opportunities for transportation is given as 0.45 job/truck (WHO, 2014). $\mathrm{CA_{truck}}$ and $\mathrm{N_{trip}}$ are assumed as 15 tonnes and 1200 trips per annum.

Table 8-6: Job employment in different processes

Process	**Job Creation**
DLF Production[1]	0.002
Energy Pack Production[1]	0.022
Pellet Production[1]	0.001
Slow Pyrolysis[2]	0.004
Fast Pyrolysis[2]	0.004
Acid Fermentation[3]	0.010
Alkaline Fermentation[3]	0.010
Hot Water Fermentation[3]	0.010
Steam Explosion Fermentation[3]	0.010
Citric Acid Production[4]	0.005
Formic Acid Production[4]	0.004
Gas Turbine[5]	0.576
Steam Turbine[2]	2.210

[1]FAO (2014); [2]Maia et al. (2011); [3]Sustek (2011); [4]Gatto (2013); [5]McDermott (2012)

To obtain the lower and upper limits for normalisation, all the individual sustainability indicators are first optimised separately and individually without considering their mutual interactions. The following objectives are optimised one by one, subjecting to the constraints represented by Equations 4.1 – 4.16, 4.18 – 4.22, 8.4 – 8.19 and 8.23 – 8.38.

$$MAX = S_{GP} \quad (8.42)$$

$$MIN = S_{CF} \quad (8.43)$$

$$MIN = S_{WF} \quad (8.44)$$

$$MIN = S_{LF} \quad (8.45)$$

$$MIN = S_{ISI} \quad (8.46)$$

$$MIN = S_{DR} \quad (8.47)$$

$$MAX = S_{JO} \quad (8.48)$$

The optimisation results and the limits of objectives are highlighted in *Table 8-9*. The maximum and minimum values of respective objectives are then selected from the optimisation results as their upper and lower limits as shown in *Table 8-7*. Next, all objectives can be normalised through Equations 8.29 – 8.35.

Table 8-7: Upper and lower limits of respective sustainability indicators

Sustainability Indicators	Upper Limit	Lower Limit
Gross Profit (million USD/y)	78.60	28.80
Carbon Footprint (107 kg CO2/y)	3.887	2.978
Water Footprint (million m3/y)	6.135	10.020
Land Footprint (103 m3)	48.053	88.089
ISI	122	180
Death Risk (death/y)	37.939	77.758
Job Opportunities (103 job)	4.916	5.393

The priority weightages derived from FANP are then adopted from Chapter 7 to integrate these objectives into a single objective function. Equation 8.36 can be rewritten as follows:

$$SI = 0.3856S_{GP}^{nor} + 0.1283S_{CF}^{nor} + 0.0779S_{WF}^{nor} + 0.0511S_{LP}^{nor} + 0.1576S_{ISI}^{nor} + 0.1092S_{DR}^{nor} + 0.0903S_{Jo}^{nor} \quad (8.49)$$

With the data collected as input, the developed mathematical model is optimised based on Equation 8.37 subject to Equations 4.1 – 4.16, 4.18 – 4.22, 8.4 – 8.19, 8.23 – 8.35, 8.41 and 8.49. The MILP model is solved using LINGO v17.0 with Global Solver. The computational time is about 0.97s and the resulted model contains a total of 495 variables, 83 binary variables and 376 constraints. An optimum integrated supply chain with an optimum *SI* of 0.8595. A maximum total profit of 67.71 million USD/y, minimum carbon footprint of 3.087×10^7 kg CO2/y, minimum water footprint of 6.570 million m^3/y, minimum land footprint of 68.969×10^3 m^3, minimum ISI of 127, minimum death risk of 37.939 death/y and maximum job opportunities of 5.340×10^3 jobs are determined as summarised in *Table 8-8*. To analyse the trade-off between objectives, the result of *SI* optimisation is compared with the result of individual optimisation of each of the objective. The change in percentage in the result are measured and shown in *Table 8-9*. Comparing to the case of gross profit optimisation, a 13.86 % of gross profit is traded off to improve the performance of the supply chain in carbon footprint, water footprint, land footprint, ISI, transportation death risk and job opportunities created, resulting an increase of 33.69 % in *SI*. It is noted that land footprint is traded-off the most, which is about 43.5 % as compared to 13.86 % of gross profit, 3.66 % of carbon footprint, 7.09 % of water footprint, 4.10 % of ISI, 0.29 % of transportation death risk and 0.46 % of job opportunities created. This is because land footprint is the least prioritised objective based on the result derived from FANP framework. In other words, stakeholders of integrated biomass supply chain have a higher tolerance towards land footprint in achieving sustainability of the system. This proves that stakeholders' preferences are captured in the model with the FANP framework, leading to a "more realistic" optimisation.

Table 8-8: Optimised result

Objective Function	Gross Profit (million USD/y)	Carbon Footprint (10^7 kg CO2/y)	Water Footprint (million m^3/y)	Land Footprint (10^3 m^3)	ISI	Death Risk (death/y)	Job Opportunities (10^3 job)	SI
Max GP	**78.60** ($\mathbf{S^U_{GP}}$)	**3.887** ($\mathbf{S^U_{CF}}$)	7.641	77.619	149	39.053	**4.916** ($\mathbf{S^L_{JO}}$)	0.6368
Min CF	57.16	**2.978** ($\mathbf{S^L_{CF}}$)	6.147	88.053	127	41.626	5.327	0.7560
Min WF	58.07	2.987	**6.135** ($\mathbf{S^L_{WF}}$)	**88.089** ($\mathbf{S^U_{LP}}$)	122	41.136	5.256	0.7617
Min LF	44.88	3.127	**10.02** ($\mathbf{S^U_{WF}}$)	**48.053** ($\mathbf{S^L_{LP}}$)	127	45.987	5.325	0.6009
Min ISI	41.79	3.062	8.090	68.753	**122** ($\mathbf{S^L_{ISI}}$)	53.116	5.257	0.5780
Min DR	**28.80** ($\mathbf{S^L_{GP}}$)	3.225	9.102	68.054	178	**37.828** ($\mathbf{S^L_{DR}}$)	5.263	0.3260
Max JO	34.52	3.152	9.329	68.138	**180** ($\mathbf{S^U_{ISI}}$)	**77.758** ($\mathbf{S^U_{DR}}$)	**5.393** ($\mathbf{S^U_{JO}}$)	0.2777
Max SI	67.71	3.087	6.570	68.969	127	37.939	5.370	0.8595

Table 8-9: Result comparison

Objective Function	Gross Profit	Carbon Footprint	Water Footprint	Land Footprint	ISI	Death Risk	Job Opportunities	SI
Max GP	**-13.86%**	-20.58%	-14.02%	-11.14%	-14.77%	-3.14%	+9.24%	+33.69%
Min CF	+18.46%	**+3.66%**	+6.88%	-21.67%	±0.00%	-9.12%	+0.81%	+12.61%
Min WF	+16.60%	+3.35%	**+7.09%**	-21.71%	+4.10%	-8.04%	+2.17%	+11.76%
Min LF	+50.87%	-1.28%	-34.43%	**+43.53%**	±0.00%	-17.74%	+0.85%	+41.67%
Min ISI	+62.02%	+0.82%	-18.79%	+0.31%	**+4.10%**	-28.78%	+2.15%	+47.28%
Min DR	+135.10%	+4.28%	-27.82%	+1.34%	-28.65%	**+0.29%**	+2.03%	+161.17%
Max JO	+96.15%	-2.06%	-29.57%	+1.22%	-29.44%	-51.35%	**-0.46%**	+206.60%

Based on the solution report, the optimum integrated supply chain is extracted and displayed in *Figure 8-6*, whereas the geographical presentation of the network is displayed in *Figure 8-5*. As shown in the figures, the optimum hub number is 2 and the hubs are located at b_2 and b_4. In hub b_2, EFB is utilised for pellet and DLF production. As wastes produced from the pineapple cannery industry, pineapple molasses and peel are converted into formic acid and biogas in the fermenter and anaerobic digester respectively. The rest of the biomass (PKS, paddy straw, rice husk and bagasse) is combusted directly to produce energy to sustain the operation of the plant. In hub b_4, there is not any waste being transported from rice mills. This because the distance between these rice mills and hub b_4 is huge, which makes the practice unfeasible in term of sustainability. To fully utilise the motor oil available, EFB is also harnessed for energy pack production. Apart from that, the remaining processing structure of hub b_4 is similar to hub b_2.

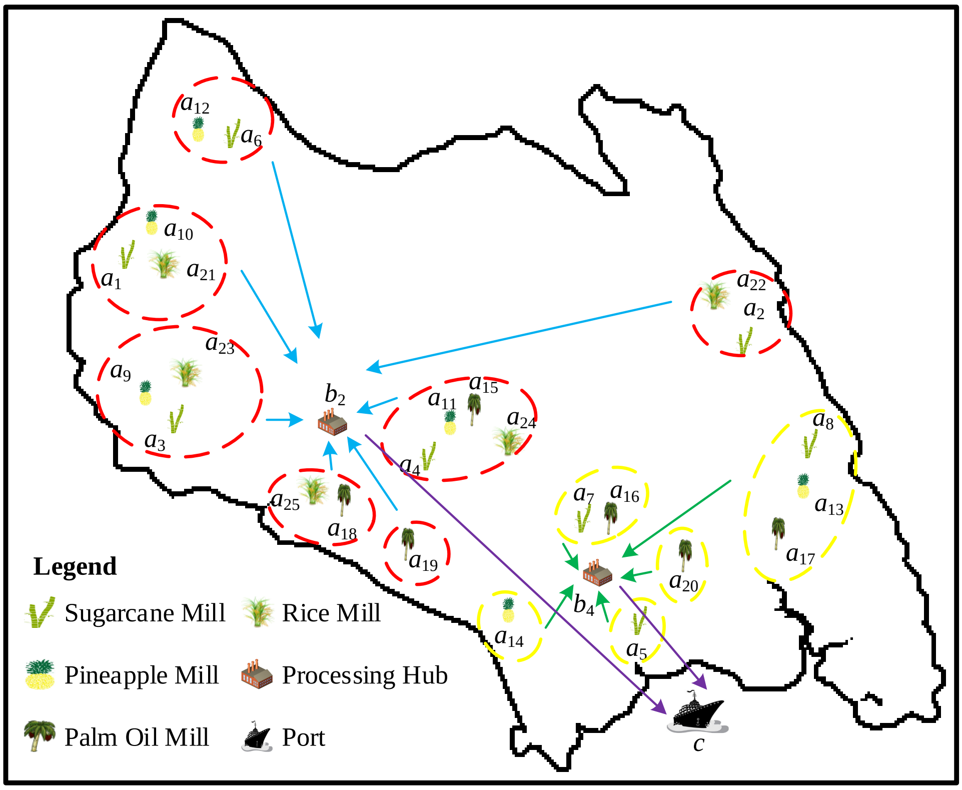

Figure 8-5: Geographical presentation of the integrated biomass supply chain

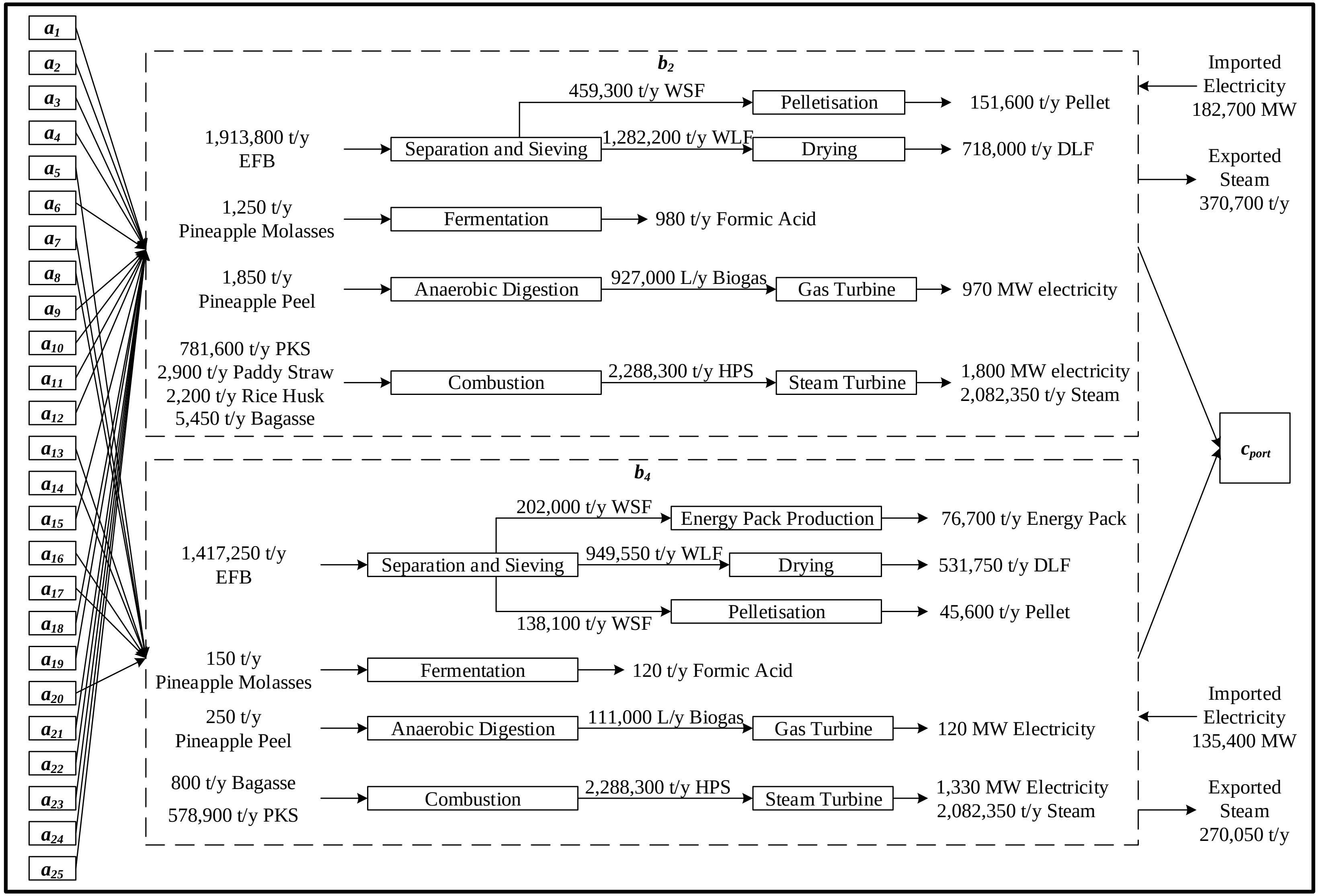

Figure 8-6: Optimum integrated biomass supply chain network

It is observed that the energy generation of the supply chain has increased gradually as compared to the base case in Chapter 4 (gross profit maximisation). It is predicted that electricity production utilising biomass is cleaner than utilising fossil fuels. When multiple footprints are accounted in the model, the processing unit tends to consume more "cleaner energy". This explains why there is a spike in electricity generation even though cost of production is higher than cost of purchasing. To verify this phenomenon, the carbon emission of power imported from the grid is varied and the energy production to energy utilisation ratio is examined. The result of the analysis is compiled in *Table 8-10*.

Table 8-10: Sensitivity analysis

Scenario	**Description**	$\frac{\textbf{Energy Produced}}{\textbf{Energy Consumed}}$
1	Max gross profit without considering carbon footprint	0.025 %
2	Max *SI* with carbon emission of power imported as 0.899 kg CO_2/kWh	1.309 %
3	Max *SI* with carbon emission of power imported as 0.800 kg CO_2/kWh	0.972 %

When optimisation does not take carbon footprint into account, the ratio of energy produced to energy consumed ratio is low, about 0.025%. The model decides to import electricity instead because the price of utility in Malaysia is cheap. As the supply chain is optimised based on its sustainability with carbon emission of power imported set at 0.899 kg CO_2/kWh power, the ratio increases to 1.309 %. The trade-off made in gross profit is compensated by carbon footprint. The ratio decreases to 0.972 % while the emission factor is adjusted to 0.800 kg CO_2/kWh power. Importing power is now considered as a "more sustainable" choice. Since the structure of the supply chain is sensitive towards objective variable, it proves that the optimisation model has successfully captured the interactions between multiple objectives. Based on the result of the analysis, it is also suggested that the government should reward carbon credits to companies that adopt cleaner production of energy as encouragement to promote the use of renewable energy.

8.7.1 Comparison with Fuzzy Optimisation Approach

In this section, the proposed ANP-aided MOO optimisation approach is compared with one of the conventional optimisation approaches, namely fuzzy optimisation approach. Fuzzy optimisation integrates multiple objectives into a single variable, the fuzzy degree of satisfaction, λ which ranges in value from 0 to 1. By introducing λ, Equations 8.29 – 8.35 and 8.37 can be rewritten as below:

$$\lambda \leq \frac{S_{GP} - \mathrm{S}_{\mathrm{GP}}^{\mathrm{L}}}{\mathrm{S}_{\mathrm{GP}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{GP}}^{\mathrm{L}}} \quad (8.50)$$

$$\lambda \leq \frac{\mathrm{S}_{\mathrm{CF}}^{\mathrm{U}} - S_{CF}}{\mathrm{S}_{\mathrm{CF}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{CF}}^{\mathrm{L}}} \quad (8.51)$$

$$\lambda \leq \frac{\mathrm{S}_{\mathrm{LF}}^{\mathrm{U}} - S_{LF}}{\mathrm{S}_{\mathrm{LF}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{LF}}^{\mathrm{L}}} \quad (8.52)$$

$$\lambda \leq \frac{\mathrm{S}_{\mathrm{WF}}^{\mathrm{U}} - S_{WF}}{\mathrm{S}_{\mathrm{WF}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{WF}}^{\mathrm{L}}} \quad (8.53)$$

$$\lambda \leq \frac{\mathrm{S}_{\mathrm{ISI}}^{\mathrm{U}} - S_{ISI}}{\mathrm{S}_{\mathrm{ISI}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{ISI}}^{\mathrm{L}}} \quad (8.54)$$

$$\lambda \leq \frac{\mathrm{S}_{\mathrm{DR}}^{\mathrm{U}} - S_{DR}}{\mathrm{S}_{\mathrm{DR}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{DR}}^{\mathrm{L}}} \quad (8.55)$$

$$\lambda \leq \frac{S_{JO} - \mathrm{S}_{\mathrm{JO}}^{\mathrm{L}}}{\mathrm{S}_{\mathrm{JO}}^{\mathrm{U}} - \mathrm{S}_{\mathrm{JO}}^{\mathrm{L}}} \quad (8.56)$$

$$MAX = \lambda \quad (8.57)$$

The fuzzy optimisation model is solved based on Equation 8.57 subject to Equations 4.1 – 4.16, 8.14 – 8.19, 8.41 and 8.50 – 8.56. The optimum results obtained from these two optimisation methods are tabulated in *Table 8-11*.

Table 8-11: Optimised results obtained from both optimisation approaches

	FANP-Aided MOO Approach	**Fuzzy Optimisation Approach**
Processing Network		
Sugarcane Bagasse	Combustion	Combustion
Pineapple Peel	Anaerobic Digestion	Anaerobic Digestion
Pineapple Molasses	Fermentation	Fermentation
Paddy Straw	Combustion	Combustion
Rice Husk	Combustion	Combustion
PKS	Combustion	Combustion
EFB	Energy Pack Production	Energy Pack Production
	Drying	Drying
	Pelletisation	Pelletisation
		Combustion
Logistic Network		
Number of Hub	2	2
Hub Selected	b_2, b_4	b_2, b_4
Sustainability Performance		
Gross Profit (million USD/y)	67.71	56.62
Carbon Footprint (10^7 kg CO_2/y)	3.087	2.98
Water Footprint (million m^3/y)	6.570	6.129
Land Footprint (10^3 m^3)	68.969	65.73
ISI	127	127
Death Risk (death/y)	37.939	49.343
Job Opportunities (10^3 job)	5.37	5.21
Sustainability Index	0.8595	0.7276

Table 8-11 shows that fuzzy optimisation model provides a more environmentally friendly solution as compared with FANP-aided MOO model. In terms of economic and social performance, result obtained from FANP-aided MOO model is better. This is because fuzzy optimisation tends to optimise the least satisfied objective, which is environmental performance in this case. Hence, fuzzy optimisation recommends partial utilisation of EFB for electricity generation via combustion which is a greener choice as compared with importing electricity. However, the drawback of self-generated electricity is more costly and less social-friendly. This is reflected on sustainability performance of these models. For logistic network, both models suggest two hubs (b_2 and b_4) as the optimum hub number.

The sustainability performance of these models is assessed through the sustainability index synthesised in Chapter 7. As shown in *Table 8-10*, FANP-aided MOO model has a higher SI score than fuzzy optimisation model. This is due to the fact that FANP-aided MOO model optimises all objectives based on stakeholders' preferences. On the other hand, fuzzy optimisation prioritises the least satisfied objective. Therefore, it can be concluded that FANP-aided MOO approach is able to provide more realistic result, which is an advantage in solving industry problems. However, it requires more effort in FANP formulation. As for fuzzy optimisation approach, it is less effort-intensive but it is only suitable for problem with multiple objectives of equal importance.

8.7.2 Model Reduction via P-graph-aided Decomposition Approach

This section discusses the advantages and disadvantages of using P-graph framework for model reduction. The P-graph-aided decomposition approach (PADA) developed in Chapter 5 is applied for model reduction of the base case synthesised previously. With all related data extracted from base case and fed into P-graph, the maximal structure generated via MSG is illustrated in *Figure 8-8*. Next, solution structures and optimum/near-optimum results are produced by SSG and ABB as presented in *Figure 8-9*. The results obtained before and after model reduction are tabulated in *Table 8-12*.

Table 8-12: Results obtained before and after model reduction via PADA

Sustainability Performance	Before Model Reduction Via PADA	After Model Reduction Via PADA	Percentage Difference (%)
Gross Profit (million USD/y)	67.71	67.29	0.6242%
Carbon Footprint (10^7 kg CO_2/y)	3.087	3.089	0.0648%
Water Footprint (million m^3/y)	6.570	6.620	0.7553%
Land Footprint (10^3 m^3)	68.969	68.965	0.0058%
ISI	127	127	0.0000%
Death Risk (death/y)	37.828	38.03	0.5312%
Job Opportunities (10^3 job)	5.37	5.36	0.1866%
Sustainability Index	0.8595	0.8546	0.5820%
Simulation Time (s)	0.97	0.094	931.91%

Based on *Figure 8-9*, the supply chain structure obtained after model reduction is exactly same as previous. However, all objectives deviate from the optimum results as observed in *Table 8-12*. As P-graph was first designed for reaction pathway synthesis, materials leaving and entering an operating unit are subject to a conversion ratio. Therefore, thinking outside the box is essential for the development of maximal structure in P-graph. *Figure 8-7* demonstrates how gross profit normalisation is done in P-graph. First, gross profit and its lower limit are inserted as raw materials. Then, deduction is done by “reacting” gross profit and lower limit with one-to-one reaction ratio whereas division is done by the “production” of normalised gross profit from gross profit with conversion ratio of $\frac{1}{\text{Upper Limit}-\text{Lower Limit}}$. Besides, some raw data needs to be processed and precalculated before being fed into P-graph. For example, conversion ratio of $\frac{1}{\text{Upper Limit}-\text{Lower Limit}}$ in the previous demonstration has to be precalculated before being input into the normalisation model. During these processes, rounding off data may cause a reduction in accuracy. This explains why the result obtained after model reduction via PADA differs from optimality. Furthermore, P-graph was only designed with a single optimisation objective, which is cost. To solve this multi-objective optimisation problem, all sustainability indicators are modelled as "intermediates" generated by different processes. All the sustainability indicators are then normalised to a single objective, SI which is presented as "product" in P-graph as shown in *Figure 8-7*.

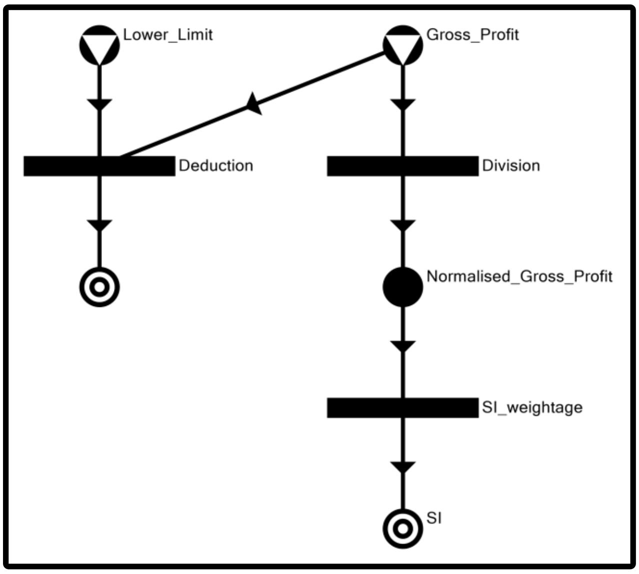

Figure 8-7: Demonstration of normalisation in P-graph

Despite tedious modelling procedures and lost in accuracy, the simulation time is reduced significantly (about 10 times faster than the original model). Other than that, its graphical feature and ability to generate near-optimum results are useful for decision-making. In conclusion, P-graph framework is effective in model reduction, especially binaries-intensive model regardless of optimality trade-off and complicated model setup.

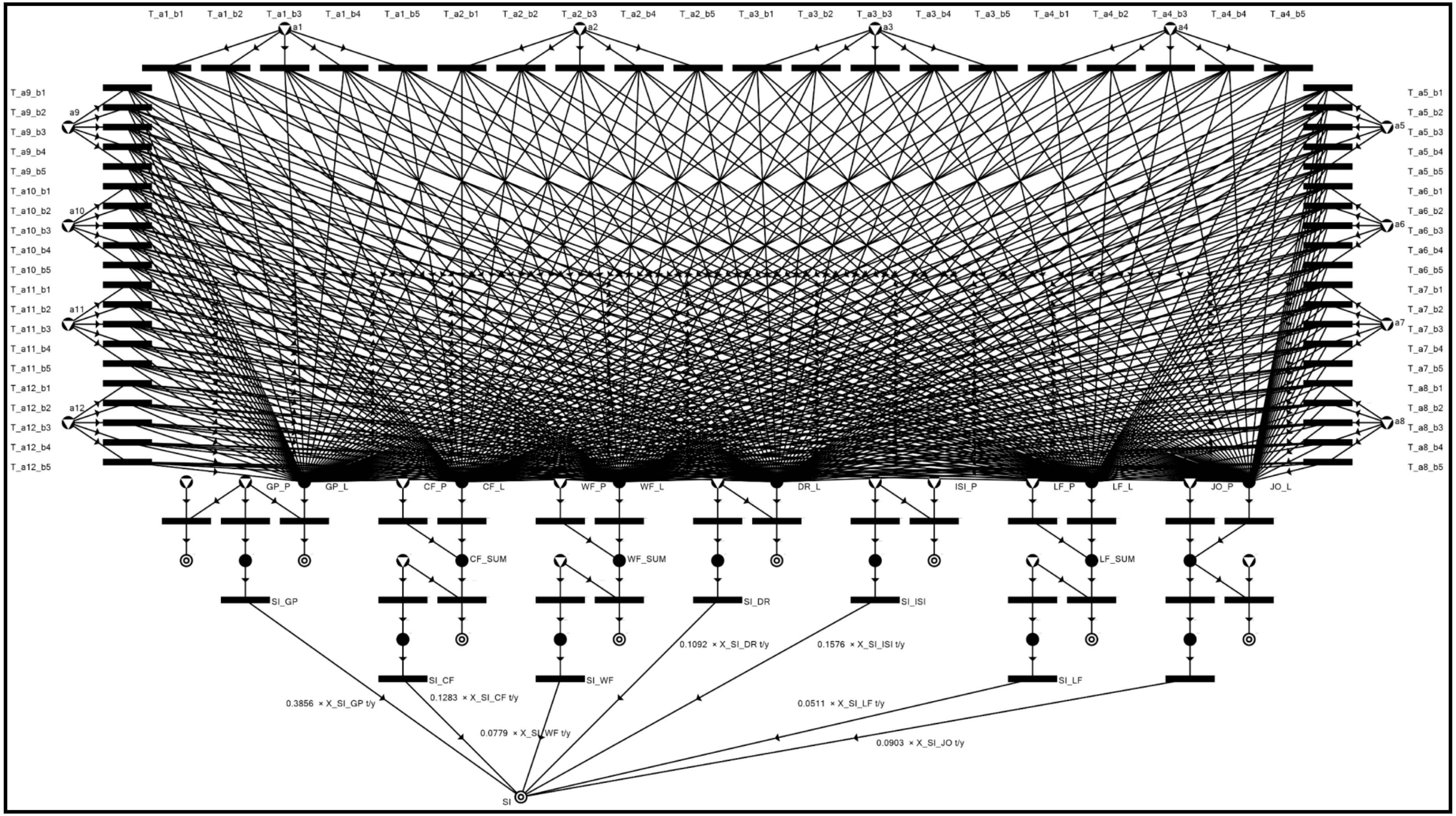

Figure 8-8: Maximal structure of integrated biomass supply chain

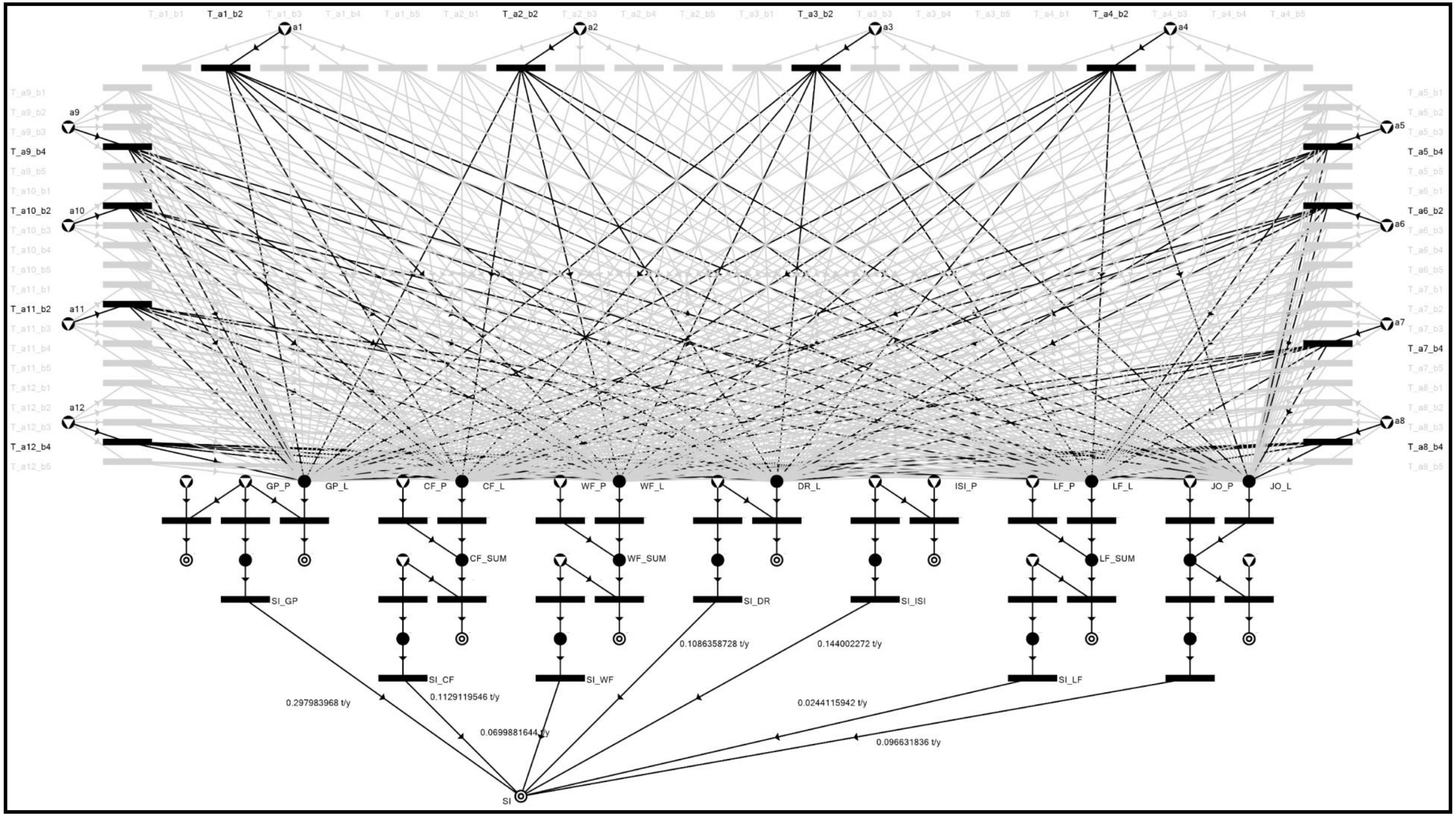

Figure 8-9: Optimum integrated biomass supply chain

8.8 Conclusion

In this chapter, a FANP-aided multiple objectives optimisation is proposed to overcome the drawback of existing optimisation models for the synthesis of integrated biomass supply chain. The FANP framework is incorporated into the model to transform multiple objective functions into single objective function by weighing each objective. It is also capable of capturing stakeholders' preferences into the model, bringing optimisation closer to reality. To ensure the comparison and trade-off between the objectives are of the same scale, max-min aggregation is adopted to normalise the objective values. The methodology has been applied to an industrial case study in Johor to demonstrate the design of a sustainable integrated biomass supply chain. The model has successfully optimised the trade-off between multiple objective functions, resulting in a "compromise" design of supply and demand network. Based on sensitivity analysis, it is suggested to offer carbon credit for the practice of cleaner production as an initiative to the development of the industry.

FANP-aided MOO approach is able to provide a solution that fulfils stakeholders' needs whereas fuzzy optimisation approach is effective in solving problem with multiple objectives of equal priority. Despite trade-off in optimality and complex modelling procedures, P-graph can reduce computational effort significantly. As all the scopes of the thesis have been completed, the concluding remark will be drawn in the next chapter. The possible future and extended work based on these scopes will also be highlighted.

CHAPTER 9

CONCLUSION AND FUTURE WORK

9.1 Conclusion

In this thesis, Chapter 1 has introduced the background of biomass utilisation and addressed the need of biomass supply chain to achieve sustainable development of the industry. The background serves as the foundation for the research conducted and theoretical development in the remaining chapters. In Chapter 2, an extensive review of biomass supply chain synthesis and optimisation is illustrated, followed by identifying and outlining research gaps. Based on the research gaps, Chapter 3 proposes several research scopes along with a research methodology. Meanwhile, Chapters 4 to 8 provide a detailed description of the contribution from this thesis, which are summarised as follows:

i. Multiple biomass corridor (MBC) concept has been introduced to incorporate multiple biomass and processing technologies into existing biomass supply chain system. The proposed approach has diversified and enriched biomass supply chain system in urban and developed regions, enhancing their flexibility, effectiveness and economic performance.

ii. P-graph-aided decomposition approach (PADA) has been presented to break down the complex and bulky biomass supply chain into two smaller subproblems. P-graph framework is adapted to reduce computational efforts to solve the binaries-intensive processing structure configuration (whether centralised or decentralised) problem. With a proper supply chain structure design determined by the approach, the economic performance of the entire system has gradually increased.

iii. To address the biomass supply chain synthesis problem in rural and remote region, resource integrated network (RIN) approach is proposed. Multiple resources (i.e. bioresources, food commodities and daily needs) are integrated into the biomass supply and demand system to improve the economic feasibility of rural biomass supply network. Inland water transportation is also incorporated to cope with the limited infrastructure problem in rural area. With distinct characteristics from urban supply chain, extended MBC and vehicle routing problem (VRP) are suggested for the synthesis of rural biomass supply chain.

iv. For the sustainability assessment of biomass supply chain, a fuzzy analytical network process-based (FANP) assessment tool is introduced. It involves stakeholders of the industry in developing a sustainability index (SI) which can be applied directly to evaluate the performance of the supply chain in terms of economic, environmental and social aspects. Fuzzy limit is also implemented in the framework to deal with the uncertainties in human judgment while conducting pairwise comparison between the elements that form the SI.

v. A novel fuzzy analytical network process-aided (FANP) multiple objectives approach is applied for the synthesis and optimisation of sustainable biomass supply chain. The FANP framework transforms the multiple objectives optimisation (MOO) problem into a single objective optimisation (SOO) problem. It has also captured the preferences of decision makers in the optimisation model, making the simulated result closer to reality. With the max-min aggregation adopted, the trade-off between multiple sustainability indicators has been successfully made.

As a whole, this thesis has successfully proposed a novel approach, from synthesis and optimisation to assessment of integrated biomass supply chain. The framework developed can be adopted as an aiding tool for development of biomass supply chain system not only in urban and developed countries but also remote and rural regions. To ensure the sustainable development of the industry, the strengths and weakness of each biomass supply chain system should be harnessed and managed respectively. Meanwhile, the external opportunities and threats of political, environmental, social and technological (PEST) aspects should be identified and made good use of. This research is just one small step in the sustainable development of the biomass industry ─ continuous effort is required for the long-term survivability of the entire industry. Lastly, the possible extension of future work of this thesis is presented.

9.2 Future Work

As concluded in Section 9.1, the work of this thesis is definitely not the end of biomass supply chain sustainable development. Future research can be conducted to enhance the competitiveness and survivability of the industry. Several potential scopes are identified for future exploration, which are summarised as follows:

i. Biomass is seasonal and weather-dependent, which makes its availability very uncertain. Besides, the quality of biomass varies from time to time. To ensure sustainable production of bioproducts, it is suggested to develop a robust optimisation approach to address these uncertainties.

ii. The biorefinery industry is relatively new industry. Hence, the technologies of the industry are not as mature as oil refinery, which has been existing for decades. For the continuous operation of the processing plant, the redundancy in supply chain design is very important. Therefore, redundancy optimisation is one of the key areas that researchers should look into.

iii. Time is a very important factor and constraint in the design of biomass supply chain. This is because the quality of biomass degrades with time, which can affect the productivity of supply chain processes. As a result, scheduling model should be proposed to minimise the production time and cost, maintaining the quality of bioproducts at the same time.

iv. The biggest challenge in the commercialisation of bioproducts is the lack of understanding of society. Besides, mismatched expectation between policy makers, researchers and industry players also hinders the development of the industry. Therefore, social research should be conducted to link stakeholders together, ensuring mutual understanding between them.

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APPENDICES

Chapter	Appendix	Section	Tittle
Chapter 4	Appendix A	Section A.1	Coding of MBC model
		Section A.2	Result of MBC model
Chapter 5	Appendix B	Section B.1	Solution structure of case study
		Section B.2	Solution structure for multiple hubs
Chapter 6	Appendix C	Section C.1	Coding of Extended MBC model
		Section C.2	Result of Extended MBC model
		Section C.3	Coding of VRP model
		Section C.4	Result of VRP model
Chapter 7	Appendix D	Section D.1	Questionnaire
		Section D.2	Pairwise comparison
		Section D.3	Coding of FANP
		Section D.4	Result of FANP
Chapter 8	Appendix E	Section E.1	Coding of MOO model
		Section E.2	Result of MOO model

APPENDICES A

CHAPTER 4 ENCHANCED GREEN ECONOMY OF URBAN AND DEVELOPED REGION VIA MULTIPLE BIOMASS CORRIDOR (MBC)

A.1 CODING OF MBC

```
MODEL:

!Multiple Biomass Corridor (MBC);

!Availability in Source A;
!Sugar cane;
a1s=1550; a2s=10; a3s=3550; a4s=50; a5s=460; a6s=270;
a7s=240; a8s=100; a9s=0; a10s=0; a11s=0; a12s=0;
!Pineapple;
a1pi=560; a2pi=0; a3pi=670; a4pi=320; a5pi=0; a6pi=1540;
a7pi=0; a8pi=170; a9pi=200; a10pi=0; a11pi=0; a12pi=0;
!Palm oil;
a1po=0; a2po=0; a3po=0; a4po=1174300; a5po=0; a6po=0;
a7po=939400; a8po=352200; a9po=0; a10po=1051400; a11po=469700; a12po=704500;
!Paddy;
a1p=2770; a2p=2610; a3p=1600; a4p=380; a5p=0; a6p=0;
a7p=0; a8p=0; a9p=0; a10p=350; a11p=0; a12p=0;
!Total biomass;
a1=a1s+a1pi+a1po+a1p;
a2=a2s+a2pi+a2po+a2p;
a3=a3s+a3pi+a3po+a3p;
a4=a4s+a4pi+a4po+a4p;
a5=a5s+a5pi+a5po+a5p;
a6=a6s+a6pi+a6po+a6p;
a7=a7s+a7pi+a7po+a7p;
a8=a8s+a8pi+a8po+a8p;
a9=a9s+a9pi+a9po+a9p;
a10=a10s+a10pi+a10po+a10p;
a11=a11s+a11pi+a11po+a11p;
a12=a12s+a12pi+a12po+a12p;


!Transfer from Source A to potential Hub B;
!5 potential hubs b1 b2 b3 b4 b5;
a1>=a1b1+a1b2+a1b3+a1b4+a1b5;
a2>=a2b1+a2b2+a2b3+a2b4+a2b5;
a3>=a3b1+a3b2+a3b3+a3b4+a3b5;
a4>=a4b1+a4b2+a4b3+a4b4+a4b5;
a5>=a5b1+a5b2+a5b3+a5b4+a5b5;
a6>=a6b1+a6b2+a6b3+a6b4+a6b5;
```

```
a7>=a7b1+a7b2+a7b3+a7b4+a7b5;
a8>=a8b1+a8b2+a8b3+a8b4+a8b5;
a9>=a9b1+a9b2+a9b3+a9b4+a9b5;
a10>=a10b1+a10b2+a10b3+a10b4+a10b5;
a11>=a11b1+a11b2+a11b3+a11b4+a11b5;
a12>=a12b1+a12b2+a12b3+a12b4+a12b5;

!Capacity Constraint of Hub B;
a1b1+a2b1+a3b1+a4b1+a5b1+a6b1+a7b1+a8b1+a9b1+a10b1+a11b1+a12b1<=4750500;
a1b2+a2b2+a3b2+a4b2+a5b2+a6b2+a7b2+a8b2+a9b2+a10b2+a11b2+a12b2<=5530800;
a1b3+a2b3+a3b3+a4b3+a5b3+a6b3+a7b3+a8b3+a9b3+a10b3+a11b3+a12b3<=4832000;
a1b4+a2b4+a3b4+a4b4+a5b4+a6b4+a7b4+a8b4+a9b4+a10b4+a11b4+a12b4<=5177000;
a1b5+a2b5+a3b5+a4b5+a5b5+a6b5+a7b5+a8b5+a9b5+a10b5+a11b5+a12b5<=4950900;

!Hub selection;
k=a1+a2+a3+a4+a5+a6+a7+a8+a9+a10+a11+a12;
bi1*(k)>=a1b1+a2b1+a3b1+a4b1+a5b1+a6b1+a7b1+a8b1+a9b1+a10b1+a11b1+a12b1;
bi2*(k)>=a1b2+a2b2+a3b2+a4b2+a5b2+a6b2+a7b2+a8b2+a9b2+a10b2+a11b2+a12b2;
bi3*(k)>=a1b3+a2b3+a3b3+a4b3+a5b3+a6b3+a7b3+a8b3+a9b3+a10b3+a11b3+a12b3;
bi4*(k)>=a1b4+a2b4+a3b4+a4b4+a5b4+a6b4+a7b4+a8b4+a9b4+a10b4+a11b4+a12b4;
bi5*(k)>=a1b5+a2b5+a3b5+a4b5+a5b5+a6b5+a7b5+a8b5+a9b5+a10b5+a11b5+a12b5;
!Number of hub required;
bi1+bi2+bi3+bi4+bi5=1;
!Binary to denote selection of particular hub;
@bin(bi1);
@bin(bi2);
@bin(bi3);
@bin(bi4);
@bin(bi5);

!Distance from source A to Hub B;
!b1;
da1b1=199;
da2b1=5;
da3b1=193;
da4b1=86;
da5b1=129;
da6b1=211;
da7b1=132;
da8b1=90;
da9b1=170;
da10b1=140;
da11b1=107;
da12b1=135;
!b2;
da1b2=95;
da2b2=109;
da3b2=89;
da4b2=24;
da5b2=86;
da6b2=93;
da7b2=63;
da8b2=115;
da9b2=75;
da10b2=33;
da11b2=32;
da12b2=72;
```

```
!b3;
da1b3=112;
da2b3=119;
da3b3=106;
da4b3=34;
da5b3=65;
da6b3=110;
da7b3=44;
da8b3=96;
da9b3=48;
da10b3=52;
da11b3=13;
da12b3=53;
!b4;
da1b4=152;
da2b4=134;
da3b4=146;
da4b4=82;
da5b4=30;
da6b4=149;
da7b4=5;
da8b4=43;
da9b4=38;
da10b4=94;
da11b4=55;
da12b4=10;
!b5;
da1b5=192;
da2b5=134;
da3b5=186;
da4b5=121;
da5b5=22;
da6b5=189;
da7b5=44;
da8b5=76;
da9b5=68;
da10b5=134;
da11b5=95;
da12b5=37;

!Logistic cost from source A to hub B;
LCab=(a1b1)*(0.2*(da1b1)+0.5)+(a2b1)*(0.2*(da2b1)+0.5)+
(a3b1)*(0.2*(da3b1)+0.5)+(a4b1)*(0.2*(da4b1)+0.5)+
(a5b1)*(0.2*(da5b1)+0.5)+(a6b1)*(0.2*(da6b1)+0.5)+
(a7b1)*(0.2*(da7b1)+0.5)+(a8b1)*(0.2*(da8b1)+0.5)+
(a9b1)*(0.2*(da9b1)+0.5)+(a10b1)*(0.2*(da10b1)+0.5)+
(a11b1)*(0.2*(da11b1)+0.5)+(a12b1)*(0.2*(da12b1)+0.5)+
(a1b2)*(0.2*(da1b2)+0.5)+(a2b2)*(0.2*(da2b2)+0.5)+
(a3b2)*(0.2*(da3b2)+0.5)+(a4b2)*(0.2*(da4b2)+0.5)+
(a5b2)*(0.2*(da5b2)+0.5)+(a6b2)*(0.2*(da6b2)+0.5)+
(a7b2)*(0.2*(da7b2)+0.5)+(a8b2)*(0.2*(da8b2)+0.5)+
(a9b2)*(0.2*(da9b2)+0.5)+(a10b2)*(0.2*(da10b2)+0.5)+
(a11b2)*(0.2*(da11b2)+0.5)+(a12b2)*(0.2*(da12b2)+0.5)+
(a1b3)*(0.2*(da1b3)+0.5)+(a2b3)*(0.2*(da2b3)+0.5)+
(a3b3)*(0.2*(da3b3)+0.5)+(a4b3)*(0.2*(da4b3)+0.5)+
(a5b3)*(0.2*(da5b3)+0.5)+(a6b3)*(0.2*(da6b3)+0.5)+
(a7b3)*(0.2*(da7b3)+0.5)+(a8b3)*(0.2*(da8b3)+0.5)+
```

```
(a9b3)*(0.2*(da9b3)+0.5)+(a10b3)*(0.2*(da10b3)+0.5)+
(a11b3)*(0.2*(da11b3)+0.5)+(a12b3)*(0.2*(da12b3)+0.5)+
(a1b4)*(0.2*(da1b4)+0.5)+(a2b4)*(0.2*(da2b4)+0.5)+
(a3b4)*(0.2*(da3b4)+0.5)+(a4b4)*(0.2*(da4b4)+0.5)+
(a5b4)*(0.2*(da5b4)+0.5)+(a6b4)*(0.2*(da6b4)+0.5)+
(a7b4)*(0.2*(da7b4)+0.5)+(a8b4)*(0.2*(da8b4)+0.5)+
(a9b4)*(0.2*(da9b4)+0.5)+(a10b4)*(0.2*(da10b4)+0.5)+
(a11b4)*(0.2*(da11b4)+0.5)+(a12b4)*(0.2*(da12b4)+0.5)+
(a1b5)*(0.2*(da1b5)+0.5)+(a2b5)*(0.2*(da2b5)+0.5)+
(a3b5)*(0.2*(da3b5)+0.5)+(a4b5)*(0.2*(da4b5)+0.5)+
(a5b5)*(0.2*(da5b5)+0.5)+(a6b5)*(0.2*(da6b5)+0.5)+
(a7b5)*(0.2*(da7b5)+0.5)+(a8b5)*(0.2*(da8b5)+0.5)+
(a9b5)*(0.2*(da9b5)+0.5)+(a10b5)*(0.2*(da10b5)+0.5)+
(a11b5)*(0.2*(da11b5)+0.5)+(a12b5)*(0.2*(da12b5)+0.5);

!Availability in Hub B;
b1+b2+b3+b4+b5=k;
b1=a1b1+a2b1+a3b1+a4b1+a5b1+a6b1+a7b1+a8b1+a9b1+a10b1+a11b1+a12b1;
b2=a1b2+a2b2+a3b2+a4b2+a5b2+a6b2+a7b2+a8b2+a9b2+a10b2+a11b2+a12b2;
b3=a1b3+a2b3+a3b3+a4b3+a5b3+a6b3+a7b3+a8b3+a9b3+a10b3+a11b3+a12b3;
b4=a1b4+a2b4+a3b4+a4b4+a5b4+a6b4+a7b4+a8b4+a9b4+a10b4+a11b4+a12b4;
b5=a1b5+a2b5+a3b5+a4b5+a5b5+a6b5+a7b5+a8b5+a9b5+a10b5+a11b5+a12b5;

!Biomass type I in Hub B;
!Sugar cane consists of only bagasse i1;
!b1;
b1s=a1b1*(a1s/(a1s+a1pi+a1po+a1p))+a2b1*(a2s/(a2s+a2pi+a2po+a2p))+
a3b1*(a3s/(a3s+a3pi+a3po+a3p))+a4b1*(a4s/(a4s+a4pi+a4po+a4p))+
a5b1*(a5s/(a5s+a5pi+a5po+a5p))+a6b1*(a6s/(a6s+a6pi+a6po+a6p))+
a7b1*(a7s/(a7s+a7pi+a7po+a7p))+a8b1*(a8s/(a8s+a8pi+a8po+a8p))+
a8b1*(a9s/(a9s+a9pi+a9po+a9p))+a10b1*(a10s/(a10s+a10pi+a10po+a10p))+
a11b1*(a11s/(a11s+a11pi+a11po+a11p))+a12b1*(a12s/(a12s+a12pi+a12po+a12p));
b1i1=b1s;
!b2;
b2s=a1b2*(a1s/(a1s+a1pi+a1po+a1p))+a2b2*(a2s/(a2s+a2pi+a2po+a2p))+
a3b2*(a3s/(a3s+a3pi+a3po+a3p))+a4b2*(a4s/(a4s+a4pi+a4po+a4p))+
a5b2*(a5s/(a5s+a5pi+a5po+a5p))+a6b2*(a6s/(a6s+a6pi+a6po+a6p))+
a7b2*(a7s/(a7s+a7pi+a7po+a7p))+a8b2*(a8s/(a8s+a8pi+a8po+a8p))+
a9b2*(a9s/(a9s+a9pi+a9po+a9p))+a10b2*(a10s/(a10s+a10pi+a10po+a10p))+
a11b2*(a11s/(a11s+a11pi+a11po+a11p))+a12b2*(a12s/(a12s+a12pi+a12po+a12p));
b2i1=b2s;
!b3;
b3s=a1b3*(a1s/(a1s+a1pi+a1po+a1p))+a2b3*(a2s/(a2s+a2pi+a2po+a2p))+
a3b3*(a3s/(a3s+a3pi+a3po+a3p))+a4b3*(a4s/(a4s+a4pi+a4po+a4p))+
a5b3*(a5s/(a5s+a5pi+a5po+a5p))+a6b3*(a6s/(a6s+a6pi+a6po+a6p))+
a7b3*(a7s/(a7s+a7pi+a7po+a7p))+a8b3*(a8s/(a8s+a8pi+a8po+a8p))+
a9b3*(a9s/(a9s+a9pi+a9po+a9p))+a10b3*(a10s/(a10s+a10pi+a10po+a10p))+
a11b3*(a11s/(a11s+a11pi+a11po+a11p))+a12b3*(a12s/(a12s+a12pi+a12po+a12p));
b3i1=b3s;
!b4;
b4s=a1b4*(a1s/(a1s+a1pi+a1po+a1p))+a2b4*(a2s/(a2s+a2pi+a2po+a2p))+
a3b4*(a3s/(a3s+a3pi+a3po+a3p))+a4b4*(a4s/(a4s+a4pi+a4po+a4p))+
a5b4*(a5s/(a5s+a5pi+a5po+a5p))+a6b4*(a6s/(a6s+a6pi+a6po+a6p))+
a7b4*(a7s/(a7s+a7pi+a7po+a7p))+a8b4*(a8s/(a8s+a8pi+a8po+a8p))+
a9b4*(a9s/(a9s+a9pi+a9po+a9p))+a10b4*(a10s/(a10s+a10pi+a10po+a10p))+
a11b4*(a11s/(a11s+a11pi+a11po+a11p))+a12b4*(a12s/(a12s+a12pi+a12po+a12p));
b4i1=b4s;
```

```
!b5;
b5s=a1b5*(a1s/(a1s+a1pi+a1po+a1p))+a2b5*(a2s/(a2s+a2pi+a2po+a2p))+
a3b5*(a3s/(a3s+a3pi+a3po+a3p))+a4b5*(a4s/(a4s+a4pi+a4po+a4p))+
a5b5*(a5s/(a5s+a5pi+a5po+a5p))+a6b5*(a6s/(a6s+a6pi+a6po+a6p))+
a7b5*(a7s/(a7s+a7pi+a7po+a7p))+a8b5*(a8s/(a8s+a8pi+a8po+a8p))+
a9b5*(a9s/(a9s+a9pi+a9po+a9p))+a10b5*(a10s/(a10s+a10pi+a10po+a10p))+
a11b5*(a11s/(a11s+a11pi+a11po+a11p))+a12b5*(a12s/(a12s+a12pi+a12po+a12p));
b5i1=b5s;

!Pineapple consists of  60% peel i2 and  40% molasses i3;
!b1;
b1pi=a1b1*(a1pi/(a1s+a1pi+a1po+a1p))+a2b1*(a2pi/(a2s+a2pi+a2po+a2p))+
a3b1*(a3pi/(a3s+a3pi+a3po+a3p))+a4b1*(a4pi/(a4s+a4pi+a4po+a4p))+
a5b1*(a5pi/(a5s+a5pi+a5po+a5p))+a6b1*(a6pi/(a6s+a6pi+a6po+a6p))+
a7b1*(a7pi/(a7s+a7pi+a7po+a7p))+a8b1*(a8pi/(a8s+a8pi+a8po+a8p))+
a9b1*(a9pi/(a9s+a9pi+a9po+a9p))+a10b1*(a10pi/(a10s+a10pi+a10po+a10p))+
a11b1*(a11pi/(a11s+a11pi+a11po+a11p))+a12b1*(a12pi/(a12s+a12pi+a12po+a12p));
b1i2=b1pi*0.6;
b1i3=b1pi*0.4;
!b2;
b2pi=a1b2*(a1pi/(a1s+a1pi+a1po+a1p))+a2b2*(a2pi/(a2s+a2pi+a2po+a2p))+
a3b2*(a3pi/(a3s+a3pi+a3po+a3p))+a4b2*(a4pi/(a4s+a4pi+a4po+a4p))+
a5b2*(a5pi/(a5s+a5pi+a5po+a5p))+a6b2*(a6pi/(a6s+a6pi+a6po+a6p))+
a7b2*(a7pi/(a7s+a7pi+a7po+a7p))+a8b2*(a8pi/(a8s+a8pi+a8po+a8p))+
a9b2*(a9pi/(a9s+a9pi+a9po+a9p))+a10b2*(a10pi/(a10s+a10pi+a10po+a10p))+
a11b2*(a11pi/(a11s+a11pi+a11po+a11p))+a12b2*(a12pi/(a12s+a12pi+a12po+a12p));
b2i2=b2pi*0.6;
b2i3=b2pi*0.4;
!b3;
b3pi=a1b3*(a1pi/(a1s+a1pi+a1po+a1p))+a2b3*(a2pi/(a2s+a2pi+a2po+a2p))+
a3b3*(a3pi/(a3s+a3pi+a3po+a3p))+a4b3*(a4pi/(a4s+a4pi+a4po+a4p))+
a5b3*(a5pi/(a5s+a5pi+a5po+a5p))+a6b3*(a6pi/(a6s+a6pi+a6po+a6p))+
a7b3*(a7pi/(a7s+a7pi+a7po+a7p))+a8b3*(a8pi/(a8s+a8pi+a8po+a8p))+
a9b3*(a9pi/(a9s+a9pi+a9po+a9p))+a10b3*(a10pi/(a10s+a10pi+a10po+a10p))+
a11b3*(a11pi/(a11s+a11pi+a11po+a11p))+a12b3*(a12pi/(a12s+a12pi+a12po+a12p));
b3i2=b3pi*0.6;
b3i3=b3pi*0.4;
!b4;
b4pi=a1b4*(a1pi/(a1s+a1pi+a1po+a1p))+a2b4*(a2pi/(a2s+a2pi+a2po+a2p))+
a3b4*(a3pi/(a3s+a3pi+a3po+a3p))+a4b4*(a4pi/(a4s+a4pi+a4po+a4p))+
a5b4*(a5pi/(a5s+a5pi+a5po+a5p))+a6b4*(a6pi/(a6s+a6pi+a6po+a6p))+
a7b4*(a7pi/(a7s+a7pi+a7po+a7p))+a8b4*(a8pi/(a8s+a8pi+a8po+a8p))+
a9b4*(a9pi/(a9s+a9pi+a9po+a9p))+a10b4*(a10pi/(a10s+a10pi+a10po+a10p))+
a11b4*(a11pi/(a11s+a11pi+a11po+a11p))+a12b4*(a12pi/(a12s+a12pi+a12po+a12p));
b4i2=b4pi*0.6;
b4i3=b4pi*0.4;
!b5;
b5pi=a1b5*(a1pi/(a1s+a1pi+a1po+a1p))+a2b5*(a2pi/(a2s+a2pi+a2po+a2p))+
a3b5*(a3pi/(a3s+a3pi+a3po+a3p))+a4b5*(a4pi/(a4s+a4pi+a4po+a4p))+
a5b5*(a5pi/(a5s+a5pi+a5po+a5p))+a6b5*(a6pi/(a6s+a6pi+a6po+a6p))+
a7b5*(a7pi/(a7s+a7pi+a7po+a7p))+a8b5*(a8pi/(a8s+a8pi+a8po+a8p))+
a9b5*(a9pi/(a9s+a9pi+a9po+a9p))+a10b5*(a10pi/(a10s+a10pi+a10po+a10p))+
a11b5*(a11pi/(a11s+a11pi+a11po+a11p))+a12b5*(a12pi/(a12s+a12pi+a12po+a12p));
b5i2=b5pi*0.6;
b5i3=b5pi*0.4;

!Palm oil consists of 71% EFB i4 and 29% PKS i5;
```

```
!b1;
b1po=a1b1*(a1po/(a1s+a1pi+a1po+a1p))+a2b1*(a2po/(a2s+a2pi+a2po+a2p))+
a3b1*(a3po/(a3s+a3pi+a3po+a3p))+a4b1*(a4po/(a4s+a4pi+a4po+a4p))+
a5b1*(a5po/(a5s+a5pi+a5po+a5p))+a6b1*(a6po/(a6s+a6pi+a6po+a6p))+
a7b1*(a7po/(a7s+a7pi+a7po+a7p))+a8b1*(a8po/(a8s+a8pi+a8po+a8p))+
a9b1*(a9po/(a9s+a9pi+a9po+a9p))+a10b1*(a10po/(a10s+a10pi+a10po+a10p))+
a11b1*(a11po/(a11s+a11pi+a11po+a11p))+a12b1*(a12po/(a12s+a12pi+a12po+a12p));
b1i4=b1po*0.71;
b1i5=b1po*0.29;
!b2;
b2po=a1b2*(a1po/(a1s+a1pi+a1po+a1p))+a2b2*(a2po/(a2s+a2pi+a2po+a2p))+
a3b2*(a3po/(a3s+a3pi+a3po+a3p))+a4b2*(a4po/(a4s+a4pi+a4po+a4p))+
a5b2*(a5po/(a5s+a5pi+a5po+a5p))+a6b2*(a6po/(a6s+a6pi+a6po+a6p))+
a7b2*(a7po/(a7s+a7pi+a7po+a7p))+a8b2*(a8po/(a8s+a8pi+a8po+a8p))+
a9b2*(a9po/(a9s+a9pi+a9po+a9p))+a10b2*(a10po/(a10s+a10pi+a10po+a10p))+
a11b2*(a11po/(a11s+a11pi+a11po+a11p))+a12b2*(a12po/(a12s+a12pi+a12po+a12p));
b2i4=b2po*0.71;
b2i5=b2po*0.29;
!b3;
b3po=a1b3*(a1po/(a1s+a1pi+a1po+a1p))+a2b3*(a2po/(a2s+a2pi+a2po+a2p))+
a3b3*(a3po/(a3s+a3pi+a3po+a3p))+a4b3*(a4po/(a4s+a4pi+a4po+a4p))+
a5b3*(a5po/(a5s+a5pi+a5po+a5p))+a6b3*(a6po/(a6s+a6pi+a6po+a6p))+
a7b3*(a7po/(a7s+a7pi+a7po+a7p))+a8b3*(a8po/(a8s+a8pi+a8po+a8p))+
a9b3*(a9po/(a9s+a9pi+a9po+a9p))+a10b3*(a10po/(a10s+a10pi+a10po+a10p))+
a11b3*(a11po/(a11s+a11pi+a11po+a11p))+a12b3*(a12po/(a12s+a12pi+a12po+a12p));
b3i4=b3po*0.71;
b3i5=b3po*0.29;
!b4;
b4po=a1b4*(a1po/(a1s+a1pi+a1po+a1p))+a2b4*(a2po/(a2s+a2pi+a2po+a2p))+
a3b4*(a3po/(a3s+a3pi+a3po+a3p))+a4b4*(a4po/(a4s+a4pi+a4po+a4p))+
a5b4*(a5po/(a5s+a5pi+a5po+a5p))+a6b4*(a6po/(a6s+a6pi+a6po+a6p))+
a7b4*(a7po/(a7s+a7pi+a7po+a7p))+a8b4*(a8po/(a8s+a8pi+a8po+a8p))+
a9b4*(a9po/(a9s+a9pi+a9po+a9p))+a10b4*(a10po/(a10s+a10pi+a10po+a10p))+
a11b4*(a11po/(a11s+a11pi+a11po+a11p))+a12b4*(a12po/(a12s+a12pi+a12po+a12p));
b4i4=b4po*0.71;
b4i5=b4po*0.29;
!b5;
b5po=a1b5*(a1po/(a1s+a1pi+a1po+a1p))+a2b5*(a2po/(a2s+a2pi+a2po+a2p))+
a3b5*(a3po/(a3s+a3pi+a3po+a3p))+a4b5*(a4po/(a4s+a4pi+a4po+a4p))+
a5b5*(a5po/(a5s+a5pi+a5po+a5p))+a6b5*(a6po/(a6s+a6pi+a6po+a6p))+
a7b5*(a7po/(a7s+a7pi+a7po+a7p))+a8b5*(a8po/(a8s+a8pi+a8po+a8p))+
a9b5*(a9po/(a9s+a9pi+a9po+a9p))+a10b5*(a10po/(a10s+a10pi+a10po+a10p))+
a11b5*(a11po/(a11s+a11pi+a11po+a11p))+a12b5*(a12po/(a12s+a12pi+a12po+a12p));
b5i4=b5po*0.71;
b5i5=b5po*0.29;

!Paddy consists of 57% paddy straw i6 and 43% rice husk i7;
!b1;
b1p=a1b1*(a1p/(a1s+a1pi+a1po+a1p))+a2b1*(a2p/(a2s+a2pi+a2po+a2p))+
a3b1*(a3p/(a3s+a3pi+a3po+a3p))+a4b1*(a4p/(a4s+a4pi+a4po+a4p))+
a5b1*(a5p/(a5s+a5pi+a5po+a5p))+a6b1*(a6p/(a6s+a6pi+a6po+a6p))+
a7b1*(a7p/(a7s+a7pi+a7po+a7p))+a8b1*(a8p/(a8s+a8pi+a8po+a8p))+
a9b1*(a9p/(a9s+a9pi+a9po+a9p))+a10b1*(a10p/(a10s+a10pi+a10po+a10p))+
a11b1*(a11p/(a11s+a11pi+a11po+a11p))+a12b1*(a12p/(a12s+a12pi+a12po+a12p));
b1i6=b1p*0.57;
b1i7=b1p*0.43;
!b2;
```

```
b2p=a1b2*(a1p/(a1s+a1pi+a1po+a1p))+a2b2*(a2po/(a2s+a2pi+a2po+a2p))+
a3b2*(a3p/(a3s+a3pi+a3po+a3p))+a4b2*(a4p/(a4s+a4pi+a4po+a4p))+
a5b2*(a5p/(a5s+a5pi+a5po+a5p))+a6b2*(a6p/(a6s+a6pi+a6po+a6p))+
a7b2*(a7p/(a7s+a7pi+a7po+a7p))+a8b2*(a8p/(a8s+a8pi+a8po+a8p))+
a9b2*(a9p/(a9s+a9pi+a9po+a9p))+a10b2*(a10p/(a10s+a10pi+a10po+a10p))+
a11b2*(a11p/(a11s+a11pi+a11po+a11p))+a12b2*(a12p/(a12s+a12pi+a12po+a12p));
b2i6=b2p*0.57;
b2i7=b2p*0.43;
!b3;
b3p=a1b3*(a1p/(a1s+a1pi+a1po+a1p))+a2b3*(a2p/(a2s+a2pi+a2po+a2p))+
a3b3*(a3p/(a3s+a3pi+a3po+a3p))+a4b3*(a4p/(a4s+a4pi+a4po+a4p))+
a5b3*(a5p/(a5s+a5pi+a5po+a5p))+a6b3*(a6p/(a6s+a6pi+a6po+a6p))+
a7b3*(a7p/(a7s+a7pi+a7po+a7p))+a8b3*(a8p/(a8s+a8pi+a8po+a8p))+
a9b3*(a9p/(a9s+a9pi+a9po+a9p))+a10b3*(a10p/(a10s+a10pi+a10po+a10p))+
a11b3*(a11p/(a11s+a11pi+a11po+a11p))+a12b3*(a12p/(a12s+a12pi+a12po+a12p));
b3i6=b3p*0.57;
b3i7=b3p*0.43;
!b4;
b4p=a1b4*(a1p/(a1s+a1pi+a1po+a1p))+a2b4*(a2p/(a2s+a2pi+a2po+a2p))+
a3b4*(a3p/(a3s+a3pi+a3po+a3p))+a4b4*(a4p/(a4s+a4pi+a4po+a4p))+
a5b4*(a5p/(a5s+a5pi+a5po+a5p))+a6b4*(a6p/(a6s+a6pi+a6po+a6p))+
a7b4*(a7p/(a7s+a7pi+a7po+a7p))+a8b4*(a8p/(a8s+a8pi+a8po+a8p))+
a9b4*(a9p/(a9s+a9pi+a9po+a9p))+a10b4*(a10p/(a10s+a10pi+a10po+a10p))+
a11b4*(a11p/(a11s+a11pi+a11po+a11p))+a12b4*(a12p/(a12s+a12pi+a12po+a12p));
b4i6=b4p*0.57;
b4i7=b4p*0.43;
!b5;
b5p=a1b5*(a1p/(a1s+a1pi+a1po+a1p))+a2b5*(a2p/(a2s+a2pi+a2po+a2p))+
a3b5*(a3p/(a3s+a3pi+a3po+a3p))+a4b5*(a4p/(a4s+a4pi+a4po+a4p))+
a5b5*(a5p/(a5s+a5pi+a5po+a5p))+a6b5*(a6p/(a6s+a6pi+a6po+a6p))+
a7b5*(a7p/(a7s+a7pi+a7po+a7p))+a8b5*(a8p/(a8s+a8pi+a8po+a8p))+
a9b5*(a9p/(a9s+a9pi+a9po+a9p))+a10b5*(a10p/(a10s+a10pi+a10po+a10p))+
a11b5*(a11p/(a11s+a11pi+a11po+a11p))+a12b5*(a12p/(a12s+a12pi+a12po+a12p));
b5i6=b5p*0.57;
b5i7=b5p*0.43;

!Technology selection in Hub B;
!Layer i to j;
!j1=combustion, j2=separation and sieving, j3=palletising,
j4= briquetting, j5=acid fermentation, j6= alkaline fermenation,
j7=hot water fermentation, j8= steam fermentation, j9=solid fermentation,
j10=liquid fermentation, j11= anaerobic digestion, j12= fast pyrolyser,
j13= slow pyrolyser,;
!b1;
b1i1=b1i1j1+b1i1j5+b1i1j6+b1i1j7+b1i1j8;
b1i2=b1i2j9+b1i2j11;
b1i3=b1i2j10;
b1i4=b1i4j1+b1i4j2+b1i4j3+b1i4j4;
b1i5=b1i5j1+b1i5j3+b1i5j4;
b1i6=b1i6j1;
b1i7=b1i7j1+b1i7j12+b1i7j13;
!b2;
b2i1=b2i1j1+b2i1j5+b2i1j6+b2i1j7+b2i1j8;
b2i2=b2i2j9+b2i2j11;
b2i3=b2i2j10;
b2i4=b2i4j1+b2i4j2+b2i4j3+b2i4j4;
b2i5=b2i5j1+b2i5j3+b2i5j4;
```

```
b2i6=b2i6j1;
b2i7=b2i7j1+b2i7j12+b2i7j13;
!b3;
b3i1=b3i1j1+b3i1j5+b3i1j6+b3i1j7+b3i1j8;
b3i2=b3i2j9+b3i2j11;
b3i3=b3i2j10;
b3i4=b3i4j1+b3i4j2+b3i4j3+b3i4j4;
b3i5=b3i5j1+b3i5j3+b3i5j4;
b3i6=b3i6j1;
b3i7=b3i7j1+b3i7j12+b3i7j13;
!b4;
b4i1=b4i1j1+b4i1j5+b4i1j6+b4i1j7+b4i1j8;
b4i2=b4i2j9+b4i2j11;
b4i3=b4i2j10;
b4i4=b4i4j1+b4i4j2+b4i4j3+b4i4j4;
b4i5=b4i5j1+b4i5j3+b4i5j4;
b4i6=b4i6j1;
b4i7=b4i7j1+b4i7j12+b4i7j13;
!b5;
b5i1=b5i1j1+b5i1j5+b5i1j6+b5i1j7+b5i1j8;
b5i2=b5i2j9+b5i2j11;
b5i3=b5i2j10;
b5i4=b5i4j1+b5i4j2+b5i4j3+b5i4j4;
b5i5=b5i5j1+b5i5j3+b5i5j4;
b5i6=b5i6j1;
b5i7=b5i7j1+b5i7j12+b5i7j13;


!Layer j to k;
!k1=HPS, k2=WLF, k3=WSF, k4= pellete, k5=briqutte, k6=ethanol, k7=citric
acid,
k8=formic acid, k9=biogas, k10=biochar, k11=syngas, k12=pyoil;
!b1;
b1k1=b1i1j1*2.2+b1i4j1*2.59+b1i5j1*3.95+b1i6j1*3.83+b1i7j1*2.59;
b1k2=b1i4j2*0.67;
b1k3=b1i4j2*0.24;
b1k3=b1k3j3+b1k3j4;
b1k4=(b1i4j3+b1i5j3+b1k3j3)*0.33;
b1k5=(b1i4j4+b1i5j4+b1k3j4)*0.33;
b1k6=b1i1j5*252.62+b1i1j6*255.8+b1i1j7*255.27+b1i1j8*230.23;
b1k7=b1i2j9*0.9;
b1k8=b1i2j10*0.79;
b1k9=b1i2j11*500;
b1k10=b1i7j12*0.26+b1i7j13*0.36;
b1k11=b1i7j12*210+b1i7j13*640;
b1k12=b1i7j12*530;
!b2;
b2k1=b2i1j1*2.2+b2i4j1*2.59+b2i5j1*3.95+b2i6j1*3.83+b2i7j1*2.59;
b2k2=b2i4j2*0.67;
b2k3=b2i4j2*0.24;
b2k3=b2k3j3+b2k3j4;
b2k4=(b2i4j3+b2i5j3+b2k3j3)*0.33;
b2k5=(b2i4j4+b2i5j4+b2k3j4)*0.33;
b2k6=b2i1j5*252.62+b2i1j6*255.8+b2i1j7*255.27+b2i1j8*230.23;
b2k7=b2i2j9*0.9;
b2k8=b2i2j10*0.79;
```

```
b2k9=b2i2j11*500;
b2k10=b2i7j12*0.26+b2i7j13*0.36;
b2k11=b2i7j12*210+b2i7j13*640;
b2k12=b2i7j12*530;
!b3;
b3k1=b3i1j1*2.2+b3i4j1*2.59+b3i5j1*3.95+b3i6j1*3.83+b3i7j1*2.59;
b3k2=b3i4j2*0.67;
b3k3=b3i4j2*0.24;
b3k3=b3k3j3+b3k3j4;
b3k4=(b3i4j3+b3i5j3+b3k3j3)*0.33;
b3k5=(b3i4j4+b3i5j4+b3k3j4)*0.33;
b3k6=b3i1j5*252.62+b3i1j6*255.8+b3i1j7*255.27+b3i1j8*230.23;
b3k7=b3i2j9*0.9;
b3k8=b3i2j10*0.79;
b3k9=b3i2j11*500;
b3k10=b3i7j12*0.26+b3i7j13*0.36;
b3k11=b3i7j12*210+b3i7j13*640;
b3k12=b3i7j12*530;
!b4;
b4k1=b4i1j1*2.2+b4i4j1*2.59+b4i5j1*3.95+b4i6j1*3.83+b4i7j1*2.59;
b4k2=b4i4j2*0.67;
b4k3=b4i4j2*0.24;
b4k3=b4k3j3+b4k3j4;
b4k4=(b4i4j3+b4i5j3+b4k3j3)*0.33;
b4k5=(b4i4j4+b4i5j4+b4k3j4)*0.33;
b4k6=b4i1j5*252.62+b4i1j6*255.8+b4i1j7*255.27+b4i1j8*230.23;
b4k7=b4i2j9*0.9;
b4k8=b4i2j10*0.79;
b4k9=b4i2j11*500;
b4k10=b4i7j12*0.26+b4i7j13*0.36;
b4k11=b4i7j12*210+b4i7j13*640;
b4k12=b4i7j12*530;
!b5;
b5k1=b5i1j1*2.2+b5i4j1*2.59+b5i5j1*3.95+b5i6j1*3.83+b5i7j1*2.59;
b5k2=b5i4j2*0.67;
b5k3=b5i4j2*0.24;
b5k3=b5k3j3+b5k3j4;
b5k4=(b5i4j3+b5i5j3+b5k3j3)*0.33;
b5k5=(b5i4j4+b5i5j4+b5k3j4)*0.33;
b5k6=b5i1j5*252.62+b5i1j6*255.8+b5i1j7*255.27+b5i1j8*230.23;
b5k7=b5i2j9*0.9;
b5k8=b5i2j10*0.79;
b5k9=b5i2j11*500;
b5k10=b5i7j12*0.26+b5i7j13*0.36;
b5k11=b5i7j12*210+b5i7j13*640;
b5k12=b5i7j12*530;

!Layer k to l;
!l1=turbine, l2=drying, l3=waste oil injection;
!b1;
b1k1=b1k1l1;
b1k2=b1k2l2;
b1k5=b1k5l3;
b1k9=b1k9l1;
!b2;
b2k1=b2k1l1;
```

```
b2k2=b2k2l2;
b2k5=b2k5l3;
b2k9=b2k9l1;
!b3;
b3k1=b3k1l1;
b3k2=b3k2l2;
b3k5=b3k5l3;
b3k9=b3k9l1;
!b4;
b4k1=b4k1l1;
b4k2=b4k2l2;
b4k5=b4k5l3;
b4k9=b4k9l1;
!b5;
b5k1=b5k1l1;
b5k2=b5k2l2;
b5k5=b5k5l3;
b5k9=b5k9l1;

!Layer l to m;
!m1=electricity, m2=MPS, m3=DLF, m4=energy pack, wo=waste oil;
!b1;
b1m1=b1k1l1*0.58+b1k9l1*1.05;
b1m2=b1k1l1*0.91;
b1m3=b1k2l2*0.56;
b1m4=b1k5l3*1.15;

!b2;
b2m1=b2k1l1*0.58+b2k9l1*1.05;
b2m2=b2k1l1*0.91;
b2m3=b2k2l2*0.56;
b2m4=b2k5l3*1.15;

!b3;
b3m1=b3k1l1*0.58+b3k9l1*1.05;
b3m2=b3k1l1*0.91;
b3m3=b3k2l2*0.56;
b3m4=b3k5l3*1.15;

!b4;
b4m1=b4k1l1*0.58+b4k9l1*1.05;
b4m2=b4k1l1*0.91;
b4m3=b4k2l2*0.56;
b4m4=b4k5l3*1.15;

!b5;
b5m1=b5k1l1*0.58+b5k9l1*1.05;
b5m2=b5k1l1*0.91;
b5m3=b5k2l2*0.56;
b5m4=b5k5l3*1.15;
!Availability of engine oil;
(b1k5l3+b2k5l3+b3k5l3+b4k5l3+b5k5l3)/10000=20/3;

!Energy balance, er=electricity required, ei=import, ex=export,
sr=steam required, si=import, sx=export;
```

```
pe=0.000789;
!b1;
b1er=220*b1m3+b1k4*180+140*b1k5+b1m4*30+(141.467*b1i1j5*252.62*pe)+(133.016*b
1i1j6*255.8*pe)+(132.74*b1i1j7*255.27*pe)+
(133.53*b1i1j8*230.23*pe)+127*b1i2j9+b1i3j10*145+b1i2j11*120+90*b1i7j12+90*b1
i7j13;
b1er=b1m1+b1ei-b1ex;
b1sr=2.8*b1m3+3*b1k4+2.8*b1k5+(1.492*b1i1j5*252.62*pe)+(1.488*b1i1j6*255.8*pe
)+(1.534*b1i1j7*255.27*pe)+(0.928*b1i1j8*230.23*pe)+
0.63*b1i2j9+b1i3j10*0.1;
b1sr=b1m2+b1si-b1sx;
!b2;
b2er=220*b2m3+b2k4*180+140*b2k5+b2m4*30+(141.467*b2i1j5*252.62*pe)+(133.016*b
2i1j6*255.8*pe)+(132.74*b2i1j7*255.27*pe)+
(133.53*b2i1j8*230.23*pe)+127*b2i2j9+b2i3j10*145+b2i2j11*120+90*b2i7j12+90*b2
i7j13;
b2er=b2m1+b2ei-b2ex;
b2sr=2.8*b2m3+3*b2k4+2.8*b2k5+(1.492*b2i1j5*252.62*pe)+(1.488*b2i1j6*255.8*pe
)+(1.534*b2i1j7*255.27*pe)+(0.928*b2i1j8*230.23*pe)+
0.63*b2i2j9+b2i3j10*0.1;
b2sr=b2m2+b2si-b2sx;
!b3;
b3er=220*b3m3+b3k4*180+140*b3k5+b3m4*30+(141.467*b3i1j5*252.62*pe)+(133.016*b
3i1j6*255.8*pe)+(132.74*b3i1j7*255.27*pe)+
(133.53*b3i1j8*230.23*pe)+127*b3i2j9+b3i3j10*145+b3i2j11*120+90*b3i7j12+90*b3
i7j13;
b3er=b3m1+b3ei-b3ex;
b3sr=2.8*b3m3+3*b3k4+2.8*b3k5+(1.492*b3i1j5*252.62*pe)+(1.488*b3i1j6*255.8*pe
)+(1.534*b3i1j7*255.27*pe)+(0.928*b3i1j8*230.23*pe)+
0.63*b3i2j9+b3i3j10*0.1;
b3sr=b3m2+b3si-b3sx;
!b4;
b4er=220*b4m3+b4k4*180+140*b4k5+b4m4*30+(141.467*b4i1j5*252.62*pe)+(133.016*b
4i1j6*255.8*pe)+(132.74*b4i1j7*255.27*pe)+
(133.53*b4i1j8*230.23*pe)+127*b4i2j9+b4i3j10*145+b4i2j11*120+90*b4i7j12+90*b4
i7j13;
b4er=b4m1+b4ei-b4ex;
b4sr=2.8*b4m3+3*b4k4+2.8*b4k5+(1.492*b4i1j5*252.62*pe)+(1.488*b4i1j6*255.8*pe
)+(1.534*b4i1j7*255.27*pe)+(0.928*b4i1j8*230.23*pe)+
0.63*b4i2j9+b4i3j10*0.1;
b4sr=b4m2+b4si-b4sx;
!b5;
b5er=220*b5m3+b5k4*180+140*b5k5+b5m4*30+(141.467*b5i1j5*252.62*pe)+(133.016*b
5i1j6*255.8*pe)+(132.74*b5i1j7*255.27*pe)+
(133.53*b5i1j8*230.23*pe)+127*b5i2j9+b5i3j10*145+b5i2j11*120+90*b5i7j12+90*b5
i7j13;
b5er=b5m1+b5ei-b5ex;
b5sr=2.8*b5m3+3*b5k4+2.8*b5k5+(1.492*b5i1j5*252.62*pe)+(1.488*b5i1j6*255.8*pe
)+(1.534*b5i1j7*255.27*pe)+(0.928*b5i1j8*230.23*pe)+
0.63*b5i2j9+b5i3j10*0.1;
b5sr=b5m2+b5si-b5sx;


!Hub profit;
!b1;
!Capital cost of hub=10 million per year;
```

```
b1uc=0.14*b1ei+6*b1si;
b1cc=b1k1*2.6+0.1*b1m1+b1m3*27.5+b1k4*27+b1k5*26.5+12.5*b1m4+(69.723*b1i1j5*2
52.62*pe)+(67.091*b1i1j6*255.8*pe)+
(43.055*b1i1j7*255.27*pe)+(39.446*b1i1j8*230.23*pe)+217.3*b1i2j9+b1i3j10*178.
18+b1i2j11*69.4+200.867*b1i7j12+
66.833*b1i7j13;
b1pr=b1ex*0.11+4*b1sx+160*b1m3+b1k4*140+130*b1m4+0.53*b1k6+700*b1k7+b1k8*450+
350*b1k10+
0.122*b1k11+0.25*b1k12;
b1gp=b1pr-b1uc-b1cc-(bi1*10000000);
!b2;
b2uc=0.14*b2ei+6*b2si;
b2cc=b2k1*2.6+0.1*b2m1+b2m3*27.5+b2k4*27+b2k5*26.5+12.5*b2m4+(69.723*b2i1j5*2
52.62*pe)+(67.091*b2i1j6*255.8*pe)+
(43.055*b2i1j7*255.27*pe)+(39.446*b2i1j8*230.23*pe)+217.3*b2i2j9+b2i3j10*178.
18+b2i2j11*69.4+200.867*b2i7j12+
66.833*b2i7j13;
b2pr=b2ex*0.11+4*b2sx+160*b2m3+b2k4*140+130*b2m4+0.53*b2k6+700*b2k7+b2k8*450+
350*b2k10+
0.122*b2k11+0.25*b2k12;
b2gp=b2pr-b2uc-b2cc-(bi2*10000000);
!b3;
b3uc=0.14*b3ei+6*b3si;
b3cc=b3k1*2.6+0.1*b3m1+b3m3*27.5+b3k4*27+b3k5*26.5+12.5*b3m4+(69.723*b3i1j5*2
52.62*pe)+(67.091*b3i1j6*255.8*pe)+
(43.055*b3i1j7*255.27*pe)+(39.446*b3i1j8*230.23*pe)+217.3*b3i2j9+b3i3j10*178.
18+b3i2j11*69.4+200.867*b3i7j12+
66.833*b3i7j13;
b3pr=b3ex*0.11+4*b3sx+160*b3m3+b3k4*140+130*b3m4+0.53*b3k6+700*b3k7+b3k8*450+
350*b3k10+
0.122*b3k11+0.25*b3k12;
b3gp=b3pr-b3uc-b3cc-(bi3*10000000);
!b4;
b4uc=0.14*b4ei+6*b4si;
b4cc=b4k1*2.6+0.1*b4m1+b4m3*27.5+b4k4*27+b4k5*26.5+12.5*b4m4+(69.723*b4i1j5*2
52.62*pe)+(67.091*b4i1j6*255.8*pe)+
(43.055*b4i1j7*255.27*pe)+(39.446*b4i1j8*230.23*pe)+217.3*b4i2j9+b4i3j10*178.
18+b4i2j11*69.4+200.867*b4i7j12+
66.833*b4i7j13;
b4pr=b4ex*0.11+4*b4sx+160*b4m3+b4k4*140+130*b4m4+0.53*b4k6+700*b4k7+b4k8*450+
350*b4k10+
0.122*b4k11+0.25*b4k12;
b4gp=b4pr-b4uc-b4cc-(bi4*10000000);
!b5;
b5uc=0.14*b5ei+6*b5si;
b5cc=b5k1*2.6+0.1*b5m1+b5m3*27.5+b5k4*27+b5k5*26.5+12.5*b5m4+(69.723*b5i1j5*2
52.62*pe)+(67.091*b5i1j6*255.8*pe)+
(43.055*b5i1j7*255.27*pe)+(39.446*b5i1j8*230.23*pe)+217.3*b5i2j9+b5i3j10*178.
18+b5i2j11*69.4+200.867*b5i7j12+
66.833*b5i7j13;
b5pr=b5ex*0.11+4*b5sx+160*b5m3+b5k4*140+130*b5m4+0.53*b5k6+700*b5k7+b5k8*450+
350*b5k10+
0.122*b5k11+0.25*b5k12;
b5gp=b5pr-b5uc-b5cc-(bi5*10000000);
```

```
!From Processing hub B to demand C;
!c=johor port;
!b1;
b1c=b1k4+(b1k6*0.000789)++b1k7+b1k8+b1k10+(b1k11*0.00095)+b1m4+b1m3;
b2c=b2k4+(b2k6*0.000789)++b2k7+b2k8+b2k10+(b2k11*0.00095)+b2m4+b2m3;
b3c=b3k4+(b3k6*0.000789)+b3k7+b3k8+b3k10+(b3k11*0.00095)+b3m4+b3m3;
b4c=b4k4+(b4k6*0.000789)++b4k7+b4k8+b4k10+(b4k11*0.00095)+b4m4+b4m3;
b5c=b5k4+(b5k6*0.000789)++b5k7+b5k8+b5k10+(b5k11*0.00095)+b5m4+b5m3;

!Distance from hub B to demand C;
db1c=138.5;
db2c=105.4;
db3c=86.5;
db4c=65.6;
db5c=10;

!Logistic cost from hub B to demand C;
LCbc=b1c*(db1c*0.2+0.5)+b2c*(db2c*0.2+0.5)+b3c*(db3c*0.2+0.5)+b4c*(db4c*0.2+0
.5)+b5c*(db5c*0.2+0.5);

!Total logictic cost;
L=LCbc+LCab;

!Objective funtion;
Max=(b3gp+b5gp+b2gp+b1gp+b4gp)-L;

END
```

A.2 Result of MBC

```
Global optimal solution found.
Objective value:                              0.6885929E+08
Objective bound:                              0.6885929E+08
Infeasibilities:                              0.5960464E-07
Extended solver steps:                                    3
Total solver iterations:                                259
Elapsed runtime seconds:                               0.05

Model Class:                                           MILP

Total variables:                   393
Nonlinear variables:                 0
Integer variables:                   5

Total constraints:                 274
Nonlinear constraints:               0

Total nonzeros:                   1355
Nonlinear nonzeros:                  0
```

Variable	Value	Reduced Cost
A1S	1550.000	0.000000
A2S	10.00000	0.000000
A3S	3550.000	0.000000
A4S	50.00000	0.000000
A5S	460.0000	0.000000
A6S	270.0000	0.000000
A7S	240.0000	0.000000
A8S	100.0000	0.000000
A9S	0.000000	0.000000
A10S	0.000000	0.000000
A11S	0.000000	0.000000
A12S	0.000000	0.000000
A1PI	560.0000	0.000000
A2PI	0.000000	0.000000
A3PI	670.0000	0.000000
A4PI	320.0000	0.000000
A5PI	0.000000	0.000000
A6PI	1540.000	0.000000
A7PI	0.000000	0.000000
A8PI	170.0000	0.000000
A9PI	200.0000	0.000000
A10PI	0.000000	0.000000
A11PI	0.000000	0.000000
A12PI	0.000000	0.000000
A1PO	0.000000	0.000000
A2PO	0.000000	0.000000
A3PO	0.000000	0.000000
A4PO	1174300.	0.000000
A5PO	0.000000	0.000000

A6PO	0.000000	0.000000
A7PO	939400.0	0.000000
A8PO	352200.0	0.000000
A9PO	0.000000	0.000000
A10PO	1051400.	0.000000
A11PO	469700.0	0.000000
A12PO	704500.0	0.000000
A1P	2770.000	0.000000
A2P	2610.000	0.000000
A3P	1600.000	0.000000
A4P	380.0000	0.000000
A5P	0.000000	0.000000
A6P	0.000000	0.000000
A7P	0.000000	0.000000
A8P	0.000000	0.000000
A9P	0.000000	0.000000
A10P	350.0000	0.000000
A11P	0.000000	0.000000
A12P	0.000000	0.000000
A1	4880.000	0.000000
A2	2620.000	0.000000
A3	5820.000	0.000000
A4	1175050.	0.000000
A5	460.0000	0.000000
A6	1810.000	0.000000
A7	939640.0	0.000000
A8	352470.0	0.000000
A9	200.0000	0.000000
A10	1051750.	0.000000
A11	469700.0	0.000000
A12	704500.0	0.000000
A1B1	0.000000	61.69346
A1B2	0.000000	63.74307
A1B3	0.000000	74.74118
A1B4	4880.000	0.000000
A1B5	0.000000	95.63832
A2B1	0.000000	16.39371
A2B2	0.000000	180.4416
A2B3	0.000000	70.44106
A2B4	2620.000	0.000000
A2B5	0.000000	79.51456
A3B1	0.000000	78.38706
A3B2	0.000000	80.42687
A3B3	0.000000	91.41939
A3B4	5820.000	0.000000
A3B5	0.000000	112.2939
A4B1	0.000000	98.84841
A4B2	0.000000	108.1948
A4B3	0.000000	117.1630
A4B4	1175050.	0.000000
A4B5	0.000000	136.9104
A5B1	0.000000	118.9639
A5B2	0.000000	133.6946
A5B3	0.000000	137.3674
A5B4	460.0000	0.000000
A5B5	0.000000	134.7762
A6B1	0.000000	4.730533

A6B2	0.000000	0.7765387
A6B3	0.000000	9.945406
A6B4	1810.000	0.000000
A6B5	0.000000	23.23844
A7B1	0.000000	123.5007
A7B2	0.000000	131.4476
A7B3	0.000000	134.6161
A7B4	939640.0	0.000000
A7B5	0.000000	136.9648
A8B1	0.000000	107.4407
A8B2	0.000000	134.1863
A8B3	0.000000	137.3541
A8B4	352470.0	0.000000
A8B5	0.000000	135.6999
A9B1	0.000000	0.000000
A9B2	0.000000	0.000000
A9B3	0.000000	0.000000
A9B4	200.0000	0.000000
A9B5	0.000000	0.000000
A10B1	0.000000	107.2817
A10B2	0.000000	107.6288
A10B3	0.000000	118.3974
A10B4	1051750.	0.000000
A10B5	0.000000	137.1464
A11B1	0.000000	108.5004
A11B2	0.000000	115.2470
A11B3	0.000000	118.4152
A11B4	469700.0	0.000000
A11B5	0.000000	137.1630
A12B1	0.000000	123.1004
A12B2	0.000000	132.2470
A12B3	0.000000	135.4152
A12B4	704500.0	0.000000
A12B5	0.000000	134.5630
K	4708900.	0.000000
BI1	0.000000	0.4928762E+09
BI2	0.000000	0.6090293E+09
BI3	0.000000	0.6496939E+09
BI4	1.000000	0.1000000E+08
BI5	0.000000	0.6925298E+09
DA1B1	199.0000	0.000000
DA2B1	5.000000	0.000000
DA3B1	193.0000	0.000000
DA4B1	86.00000	0.000000
DA5B1	129.0000	0.000000
DA6B1	211.0000	0.000000
DA7B1	132.0000	0.000000
DA8B1	90.00000	0.000000
DA9B1	170.0000	0.000000
DA10B1	140.0000	0.000000
DA11B1	107.0000	0.000000
DA12B1	135.0000	0.000000
DA1B2	95.00000	0.000000
DA2B2	109.0000	0.000000
DA3B2	89.00000	0.000000
DA4B2	24.00000	0.000000
DA5B2	86.00000	0.000000

DA6B2	93.00000	0.000000
DA7B2	63.00000	0.000000
DA8B2	115.0000	0.000000
DA9B2	75.00000	0.000000
DA10B2	33.00000	0.000000
DA11B2	32.00000	0.000000
DA12B2	72.00000	0.000000
DA1B3	112.0000	0.000000
DA2B3	119.0000	0.000000
DA3B3	106.0000	0.000000
DA4B3	34.00000	0.000000
DA5B3	65.00000	0.000000
DA6B3	110.0000	0.000000
DA7B3	44.00000	0.000000
DA8B3	96.00000	0.000000
DA9B3	48.00000	0.000000
DA10B3	52.00000	0.000000
DA11B3	13.00000	0.000000
DA12B3	53.00000	0.000000
DA1B4	152.0000	0.000000
DA2B4	134.0000	0.000000
DA3B4	146.0000	0.000000
DA4B4	82.00000	0.000000
DA5B4	30.00000	0.000000
DA6B4	149.0000	0.000000
DA7B4	5.000000	0.000000
DA8B4	43.00000	0.000000
DA9B4	38.00000	0.000000
DA10B4	94.00000	0.000000
DA11B4	55.00000	0.000000
DA12B4	10.00000	0.000000
DA1B5	192.0000	0.000000
DA2B5	134.0000	0.000000
DA3B5	186.0000	0.000000
DA4B5	121.0000	0.000000
DA5B5	22.00000	0.000000
DA6B5	189.0000	0.000000
DA7B5	44.00000	0.000000
DA8B5	76.00000	0.000000
DA9B5	68.00000	0.000000
DA10B5	134.0000	0.000000
DA11B5	95.00000	0.000000
DA12B5	37.00000	0.000000
LCAB	0.5239148E+08	0.000000
B1	0.000000	0.000000
B2	0.000000	0.000000
B3	0.000000	0.000000
B4	4708900.	0.000000
B5	0.000000	0.000000
B1S	0.000000	0.000000
B1I1	0.000000	0.000000
B2S	0.000000	0.000000
B2I1	0.000000	0.000000
B3S	0.000000	0.000000
B3I1	0.000000	0.000000
B4S	6230.000	0.000000
B4I1	6230.000	0.000000

B5S	0.000000	0.000000
B5I1	0.000000	0.000000
B1PI	0.000000	0.000000
B1I2	0.000000	0.000000
B1I3	0.000000	0.000000
B2PI	0.000000	0.000000
B2I2	0.000000	0.000000
B2I3	0.000000	0.000000
B3PI	0.000000	0.000000
B3I2	0.000000	0.000000
B3I3	0.000000	0.000000
B4PI	3460.000	0.000000
B4I2	2076.000	0.000000
B4I3	1384.000	0.000000
B5PI	0.000000	0.000000
B5I2	0.000000	0.000000
B5I3	0.000000	0.000000
B1PO	0.000000	0.000000
B1I4	0.000000	0.000000
B1I5	0.000000	0.000000
B2PO	0.000000	0.000000
B2I4	0.000000	0.000000
B2I5	0.000000	0.000000
B3PO	0.000000	0.000000
B3I4	0.000000	0.000000
B3I5	0.000000	0.000000
B4PO	4691500.	0.000000
B4I4	3330965.	0.000000
B4I5	1360535.	0.000000
B5PO	0.000000	0.000000
B5I4	0.000000	0.000000
B5I5	0.000000	0.000000
B1P	0.000000	0.000000
B1I6	0.000000	0.000000
B1I7	0.000000	0.000000
B2P	0.000000	0.000000
B2I6	0.000000	0.000000
B2I7	0.000000	0.000000
B3P	0.000000	0.000000
B3I6	0.000000	0.000000
B3I7	0.000000	0.000000
B4P	7710.000	0.000000
B4I6	4394.700	0.000000
B4I7	3315.300	0.000000
B5P	0.000000	0.000000
B5I6	0.000000	0.000000
B5I7	0.000000	0.000000
B1I1J1	0.000000	113.0339
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B1I2J9	0.000000	0.000000
B1I2J11	0.000000	537.5501
B1I2J10	0.000000	0.000000
B1I4J1	0.000000	24.38144
B1I4J2	0.000000	0.000000

B1I4J3	0.000000	11.46342
B1I4J4	0.000000	11.46342
B1I5J1	0.000000	4.957977
B1I5J3	0.000000	0.000000
B1I5J4	0.000000	0.000000
B1I6J1	0.000000	0.000000
B1I7J1	0.000000	231.9640
B1I7J12	0.000000	0.000000
B1I7J13	0.000000	75.10150
B2I1J1	0.000000	114.3700
B2I1J5	0.000000	1.760946
B2I1J6	0.000000	0.000000
B2I1J7	0.000000	0.8792927
B2I1J8	0.000000	12.71144
B2I2J9	0.000000	0.000000
B2I2J11	0.000000	543.5081
B2I2J10	0.000000	0.000000
B2I4J1	0.000000	27.46821
B2I4J2	0.000000	0.000000
B2I4J3	0.000000	12.03790
B2I4J4	0.000000	12.03790
B2I5J1	0.000000	7.470267
B2I5J3	0.000000	0.000000
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B3I1J5	0.000000	1.770430
B3I1J6	0.000000	0.000000
B3I1J7	0.000000	0.8808733
B3I1J8	0.000000	12.78770
B3I2J9	0.000000	0.000000
B3I2J11	0.000000	546.9101
B3I2J10	0.000000	0.000000
B3I4J1	0.000000	29.23075
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B3I4J3	0.000000	12.36593
B3I4J4	0.000000	12.36593
B3I5J1	0.000000	8.904777
B3I5J3	0.000000	0.000000
B3I5J4	0.000000	0.000000
B3I6J1	0.000000	0.000000
B3I7J1	0.000000	236.7428
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B3I7J13	0.000000	69.81310
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B4I1J7	6230.000	0.000000
B4I1J8	0.000000	10.30654
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B4I2J11	0.000000	444.0820
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B4I4J1	0.000000	23.72622
B4I4J2	3330965.	0.000000

B4I4J3	0.000000	12.65431
B4I4J4	0.000000	12.65431
B4I5J1	0.000000	7.150760
B4I5J3	1158515.	0.000000
B4I5J4	202020.2	0.000000
B4I6J1	4394.700	0.000000
B4I7J1	0.000000	103.9954
B4I7J12	0.000000	0.000000
B4I7J13	3315.300	0.000000
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B5I2J9	0.000000	0.000000
B5I2J11	0.000000	560.6801
B5I2J10	0.000000	0.000000
B5I4J1	0.000000	36.36484
B5I4J2	0.000000	0.000000
B5I4J3	0.000000	13.69366
B5I4J4	0.000000	13.69366
B5I5J1	0.000000	14.71113
B5I5J3	0.000000	0.000000
B5I5J4	0.000000	0.000000
B5I6J1	0.000000	0.000000
B5I7J1	0.000000	243.7732
B5I7J12	0.000000	0.000000
B5I7J13	0.000000	62.03305
B1K1	0.000000	0.000000
B1K2	0.000000	0.000000
B1K3	0.000000	0.000000
B1K3J3	0.000000	0.000000
B1K3J4	0.000000	0.000000
B1K4	0.000000	13.31550
B1K5	0.000000	0.000000
B1K6	0.000000	0.000000
B1K7	0.000000	0.000000
B1K8	0.000000	0.000000
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B1K11	0.000000	0.000000
B1K12	0.000000	0.000000
B2K1	0.000000	0.000000
B2K2	0.000000	0.000000
B2K3	0.000000	0.000000
B2K3J3	0.000000	0.000000
B2K3J4	0.000000	0.000000
B2K4	0.000000	14.30850
B2K5	0.000000	0.000000
B2K6	0.000000	0.000000
B2K7	0.000000	0.000000
B2K8	0.000000	0.000000
B2K9	0.000000	0.000000
B2K10	0.000000	0.000000
B2K11	0.000000	0.000000
B2K12	0.000000	0.000000
B3K1	0.000000	0.000000

B3K2	0.000000	0.000000
B3K3	0.000000	0.000000
B3K3J3	0.000000	0.000000
B3K3J4	0.000000	0.000000
B3K4	0.000000	14.87550
B3K5	0.000000	0.000000
B3K6	0.000000	0.000000
B3K7	0.000000	0.000000
B3K8	0.000000	0.000000
B3K9	0.000000	0.000000
B3K10	0.000000	0.000000
B3K11	0.000000	0.000000
B3K12	0.000000	0.000000
B4K1	16831.70	0.000000
B4K2	2231747.	0.000000
B4K3	799431.6	0.000000
B4K3J3	799431.6	0.000000
B4K3J4	0.000000	0.000000
B4K4	646122.3	0.000000
B4K5	66666.67	0.000000
B4K6	1590332.	0.000000
B4K7	1868.400	0.000000
B4K8	1093.360	0.000000
B4K9	0.000000	0.000000
B4K10	1193.508	0.000000
B4K11	2121792.	0.000000
B4K12	0.000000	0.1548457
B5K1	0.000000	0.000000
B5K2	0.000000	0.000000
B5K3	0.000000	0.000000
B5K3J3	0.000000	0.000000
B5K3J4	0.000000	0.000000
B5K4	0.000000	17.17050
B5K5	0.000000	0.000000
B5K6	0.000000	0.000000
B5K7	0.000000	0.000000
B5K8	0.000000	0.000000
B5K9	0.000000	0.000000
B5K10	0.000000	0.000000
B5K11	0.000000	0.000000
B5K12	0.000000	0.000000
B1K1L1	0.000000	0.000000
B1K2L2	0.000000	0.000000
B1K5L3	0.000000	0.000000
B1K9L1	0.000000	0.000000
B2K1L1	0.000000	0.000000
B2K2L2	0.000000	0.000000
B2K5L3	0.000000	0.000000
B2K9L1	0.000000	0.000000
B3K1L1	0.000000	0.000000
B3K2L2	0.000000	0.000000
B3K5L3	0.000000	0.000000
B3K9L1	0.000000	0.000000
B4K1L1	16831.70	0.000000
B4K2L2	2231747.	0.000000
B4K5L3	66666.67	0.000000
B4K9L1	0.000000	0.000000

B5K1L1	0.000000	0.000000
B5K2L2	0.000000	0.000000
B5K5L3	0.000000	0.000000
B5K9L1	0.000000	0.000000
B1M1	0.000000	0.000000
B1M2	0.000000	0.000000
B1M3	0.000000	0.000000
B1M4	0.000000	0.000000
B2M1	0.000000	0.000000
B2M2	0.000000	0.000000
B2M3	0.000000	0.000000
B2M4	0.000000	0.000000
B3M1	0.000000	0.000000
B3M2	0.000000	0.000000
B3M3	0.000000	0.000000
B3M4	0.000000	0.000000
B4M1	9762.387	0.000000
B4M2	15316.85	0.000000
B4M3	1249778.	0.000000
B4M4	76666.67	0.000000
B5M1	0.000000	0.000000
B5M2	0.000000	0.000000
B5M3	0.000000	0.000000
B5M4	0.000000	0.000000
PE	0.7890000E-03	0.000000
B1ER	0.000000	0.000000
B1I3J10	0.000000	0.000000
B1EI	0.000000	0.000000
B1EX	0.000000	0.3000000E-01
B1SR	0.000000	0.000000
B1SI	0.000000	0.000000
B1SX	0.000000	2.000000
B2ER	0.000000	0.000000
B2I3J10	0.000000	0.000000
B2EI	0.000000	0.000000
B2EX	0.000000	0.3000000E-01
B2SR	0.000000	0.000000
B2SI	0.000000	0.000000
B2SX	0.000000	2.000000
B3ER	0.000000	0.000000
B3I3J10	0.000000	0.000000
B3EI	0.000000	0.000000
B3EX	0.000000	0.3000000E-01
B3SR	0.000000	0.000000
B3SI	0.000000	0.000000
B3SX	0.000000	2.000000
B4ER	0.4036151E+09	0.000000
B4I3J10	0.000000	199.0800
B4EI	0.4036053E+09	0.000000
B4EX	0.000000	0.3000000E-01
B4SR	5627645.	0.000000
B4SI	5612328.	0.000000
B4SX	0.000000	2.000000
B5ER	0.000000	0.000000
B5I3J10	0.000000	0.000000
B5EI	0.000000	0.000000
B5EX	0.000000	0.3000000E-01

B5SR	0.000000	0.000000
B5SI	0.000000	0.000000
B5SX	0.000000	2.000000
B1UC	0.000000	0.000000
B1CC	0.000000	1.117297
B1PR	0.000000	0.000000
B1GP	0.000000	0.000000
B2UC	0.000000	0.000000
B2CC	0.000000	1.117297
B2PR	0.000000	0.000000
B2GP	0.000000	0.000000
B3UC	0.000000	0.000000
B3CC	0.000000	1.117297
B3PR	0.000000	0.000000
B3GP	0.000000	0.000000
B4UC	0.9017872E+08	0.000000
B4CC	0.5531065E+08	0.000000
B4PR	0.3037076E+09	0.000000
B4GP	0.1482183E+09	0.000000
B5UC	0.000000	0.000000
B5CC	0.000000	1.117297
B5PR	0.000000	0.000000
B5GP	0.000000	0.000000
B1C	0.000000	0.000000
B2C	0.000000	0.000000
B3C	0.000000	0.000000
B4C	1979993.	0.000000
B5C	0.000000	0.000000
DB1C	138.5000	0.000000
DB2C	105.4000	0.000000
DB3C	86.50000	0.000000
DB4C	65.60000	0.000000
DB5C	10.00000	0.000000
LCBC	0.2696750E+08	0.000000
L	0.7935898E+08	0.000000

APPENDICES B

CHAPTER 5 P-GRAPH AIDED DECOMPOSITION APPROACH (PADA) FOR THE CENTRALISATION AND DECENTRALISATION OF BIOMASS SUPPLY CHAIN

B.1 Solution Structure of Case Study

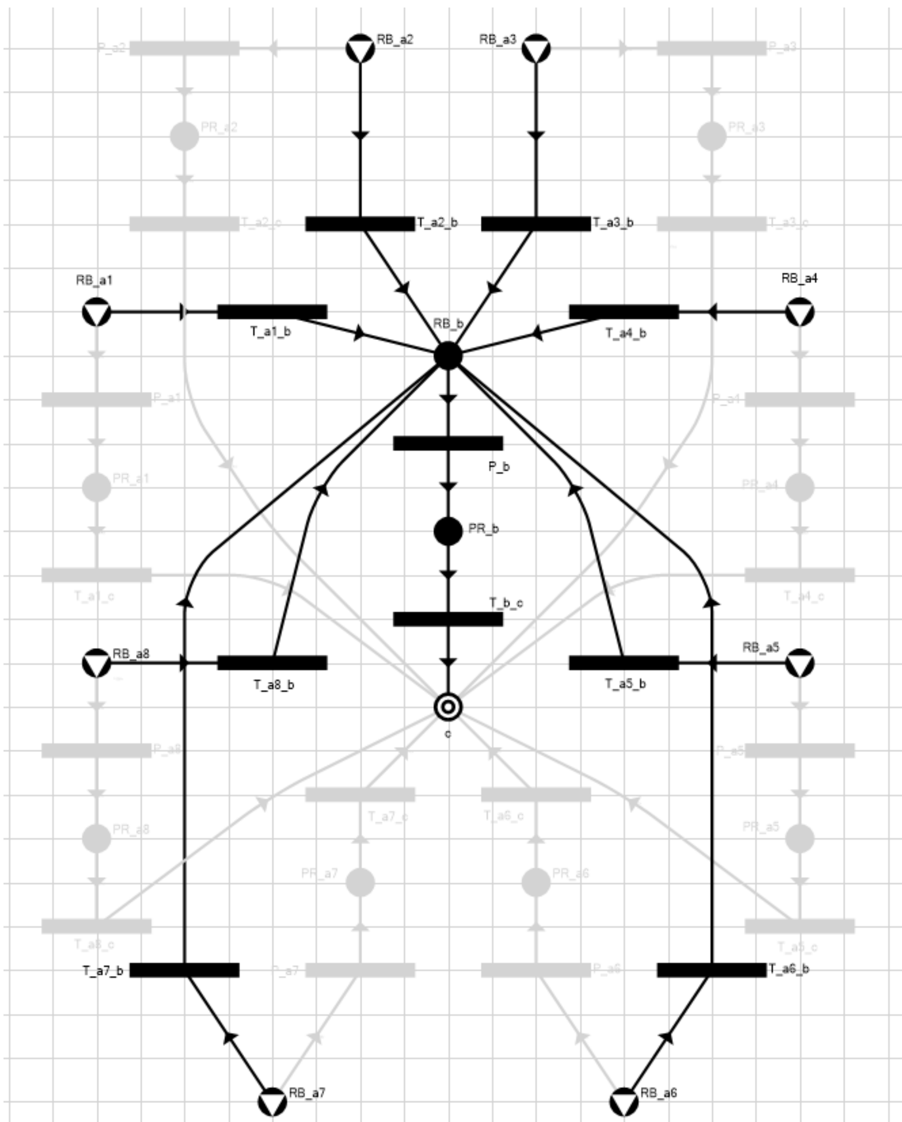

Figure A-1: Solution structure of sugarcane biomass supply chain

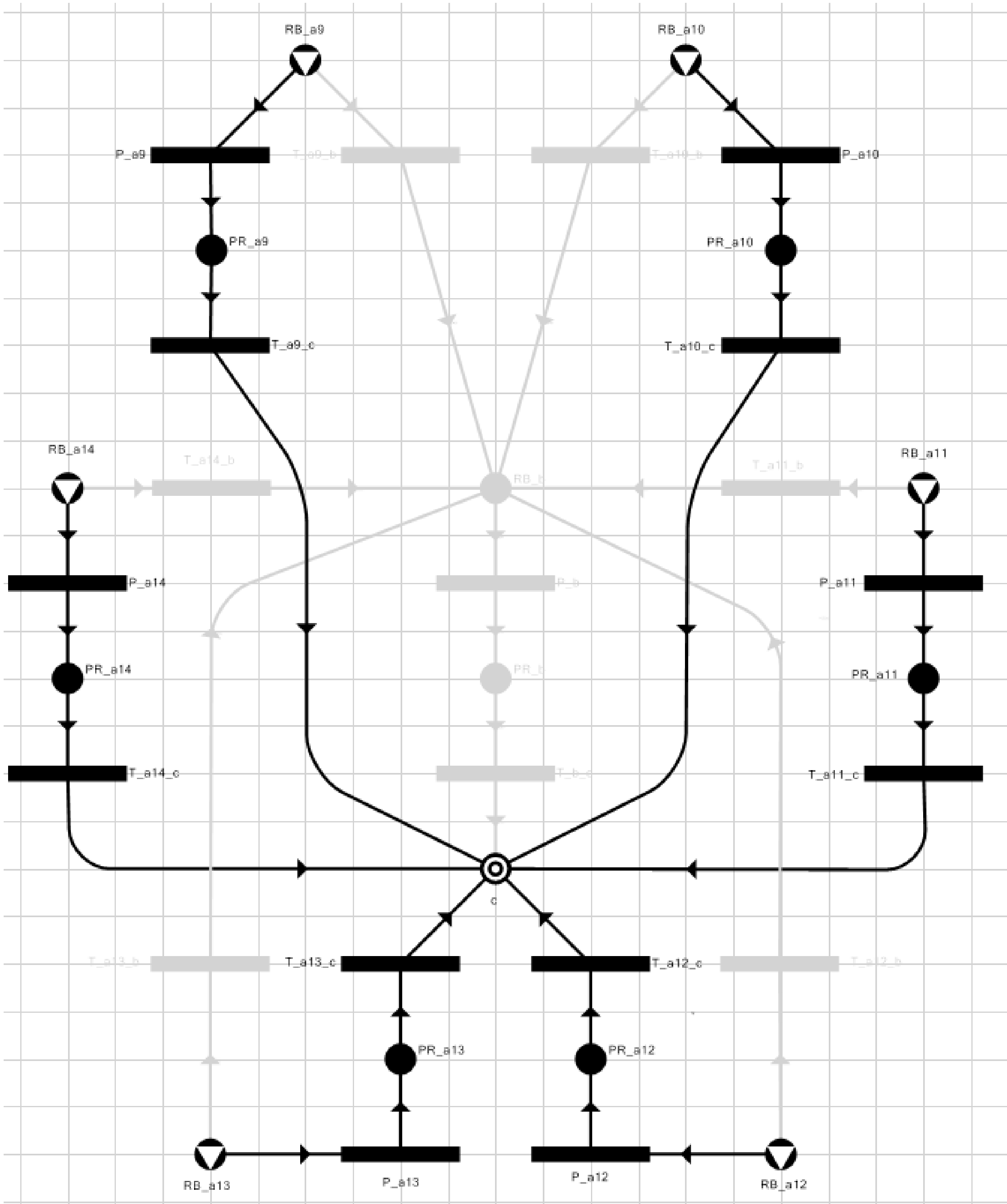

Figure A-2: Solution structure of pineapple biomass supply chain

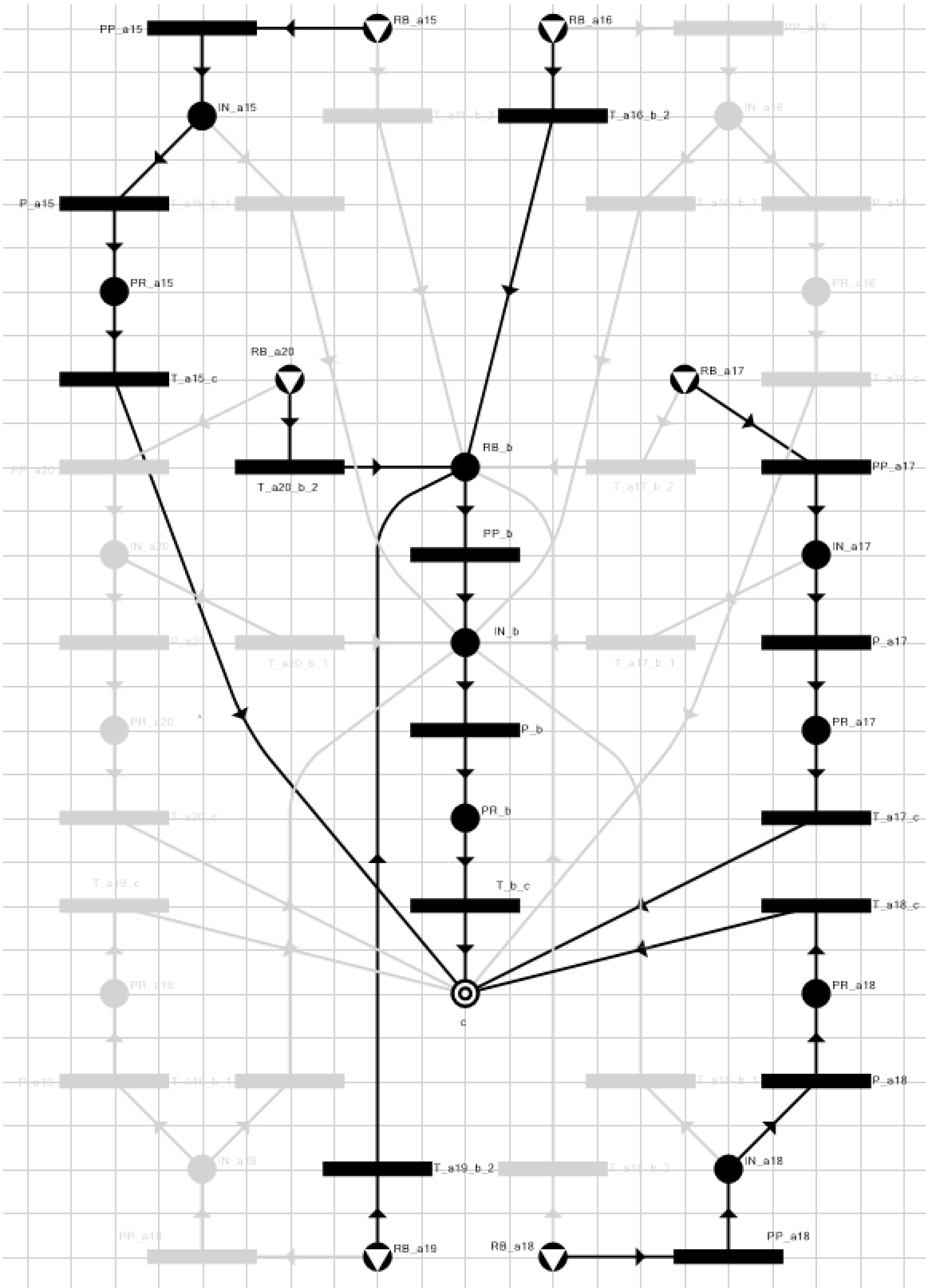

Figure A-3: Solution structure of palm oil biomass supply chain

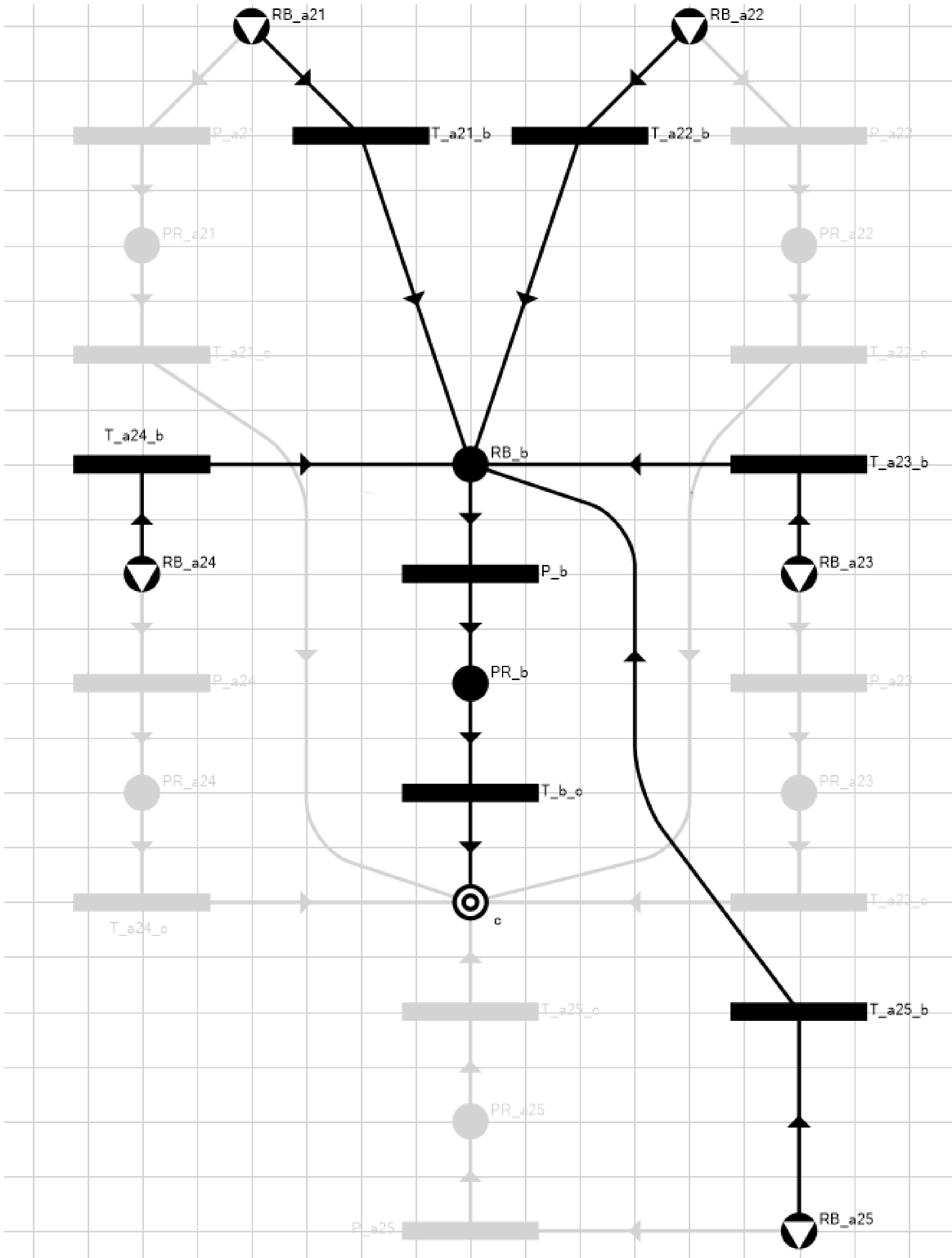

Figure A-4: Solution structure of paddy biomass supply chain

B.2 Solution Structure of Case Study

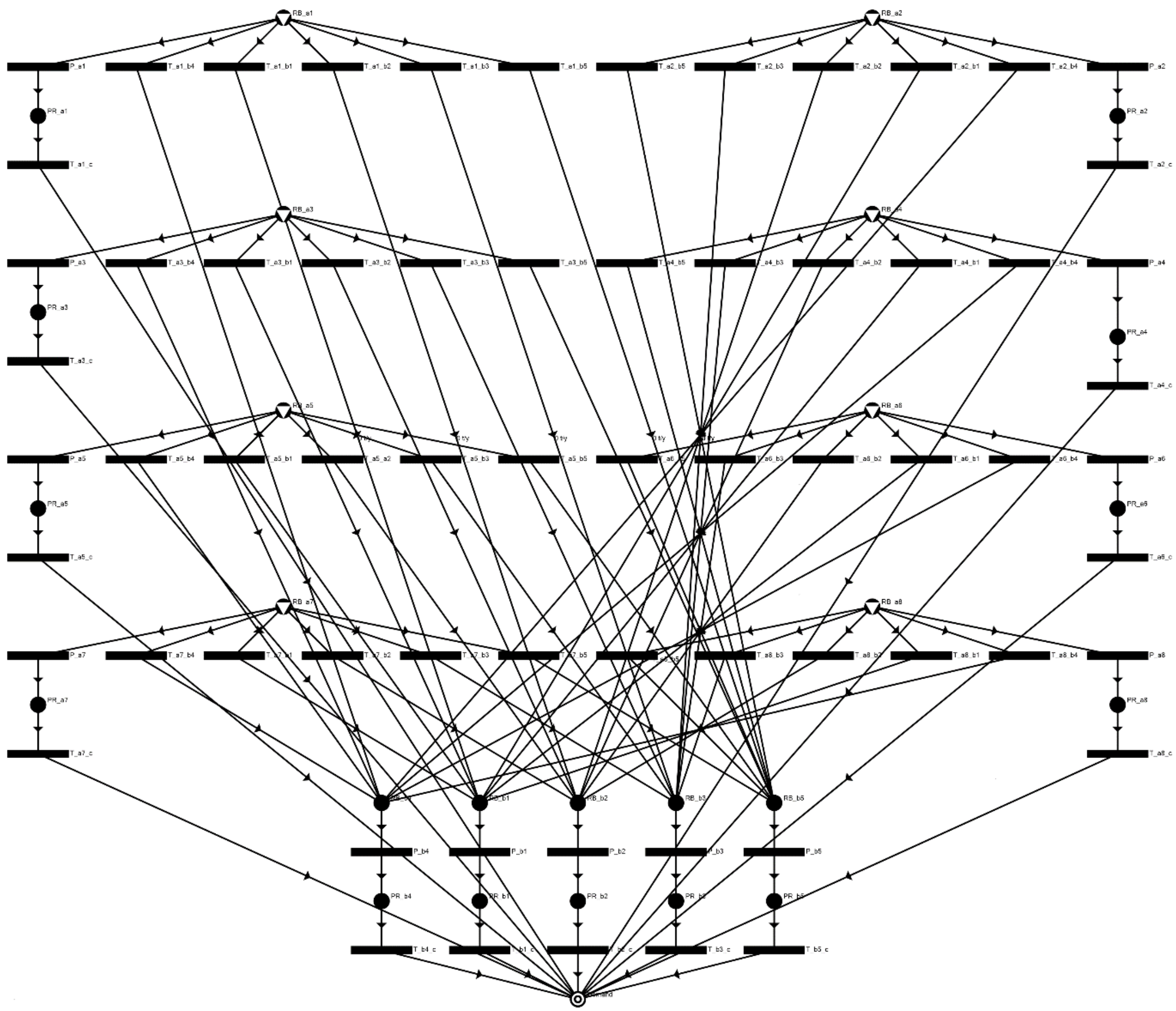

Figure A-5: Maximal structure for sugarcane biomass supply chain with multiple hubs

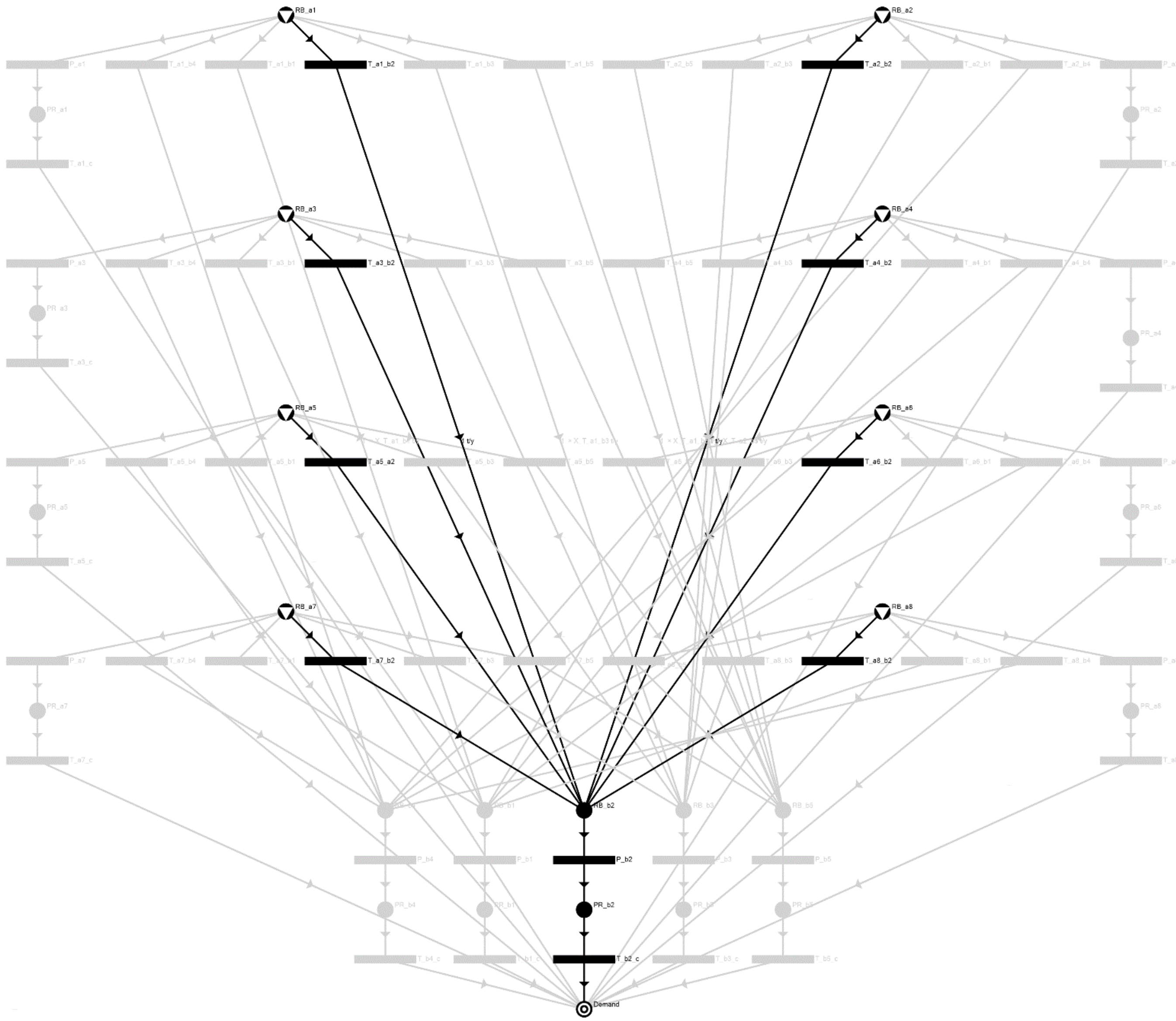

Figure A-6: Optimum structure for sugarcane biomass supply chain with multiple hubs

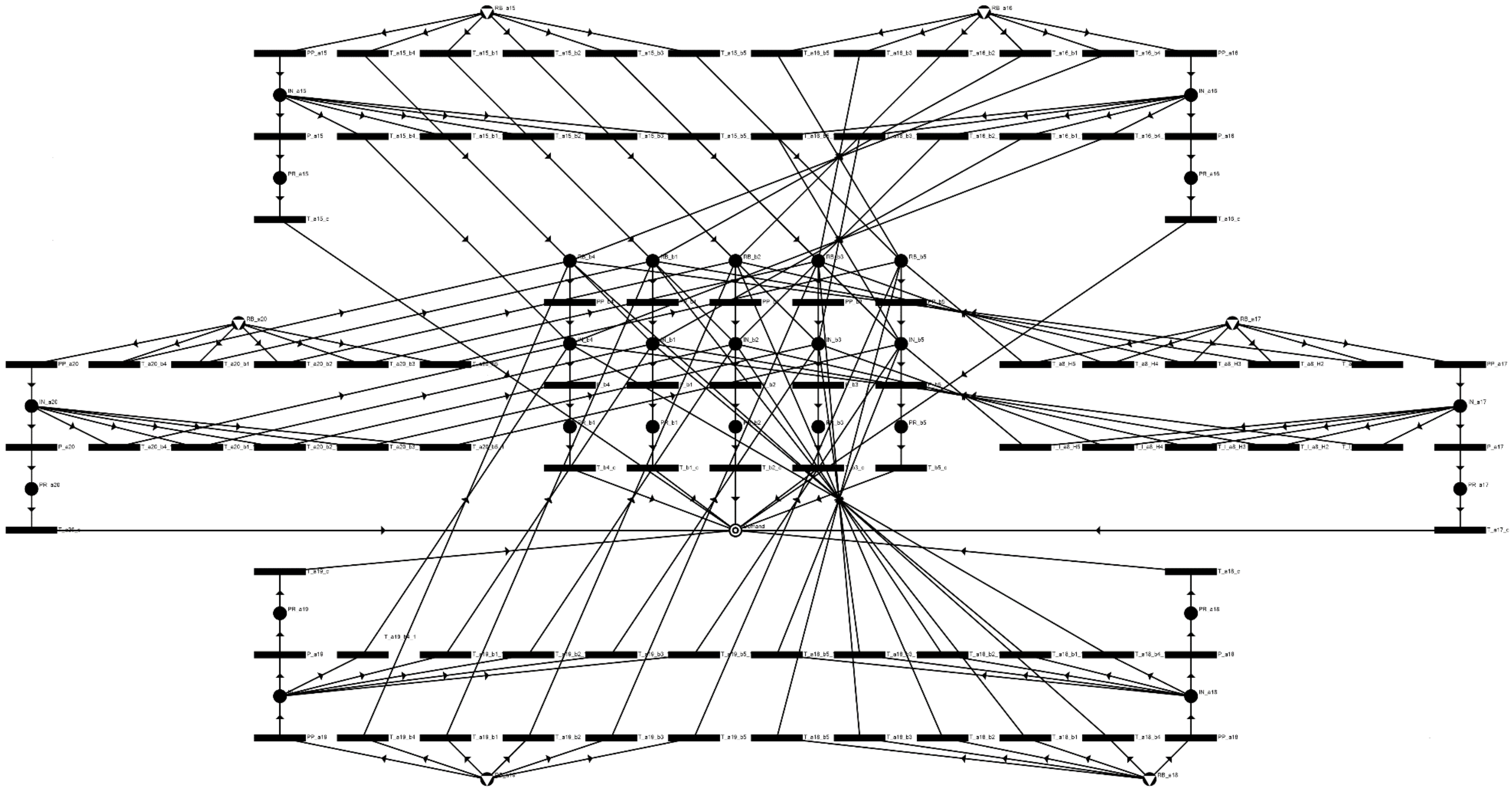

Figure A-7: Maximum structure for palm oil biomass supply chain with multiple hubs

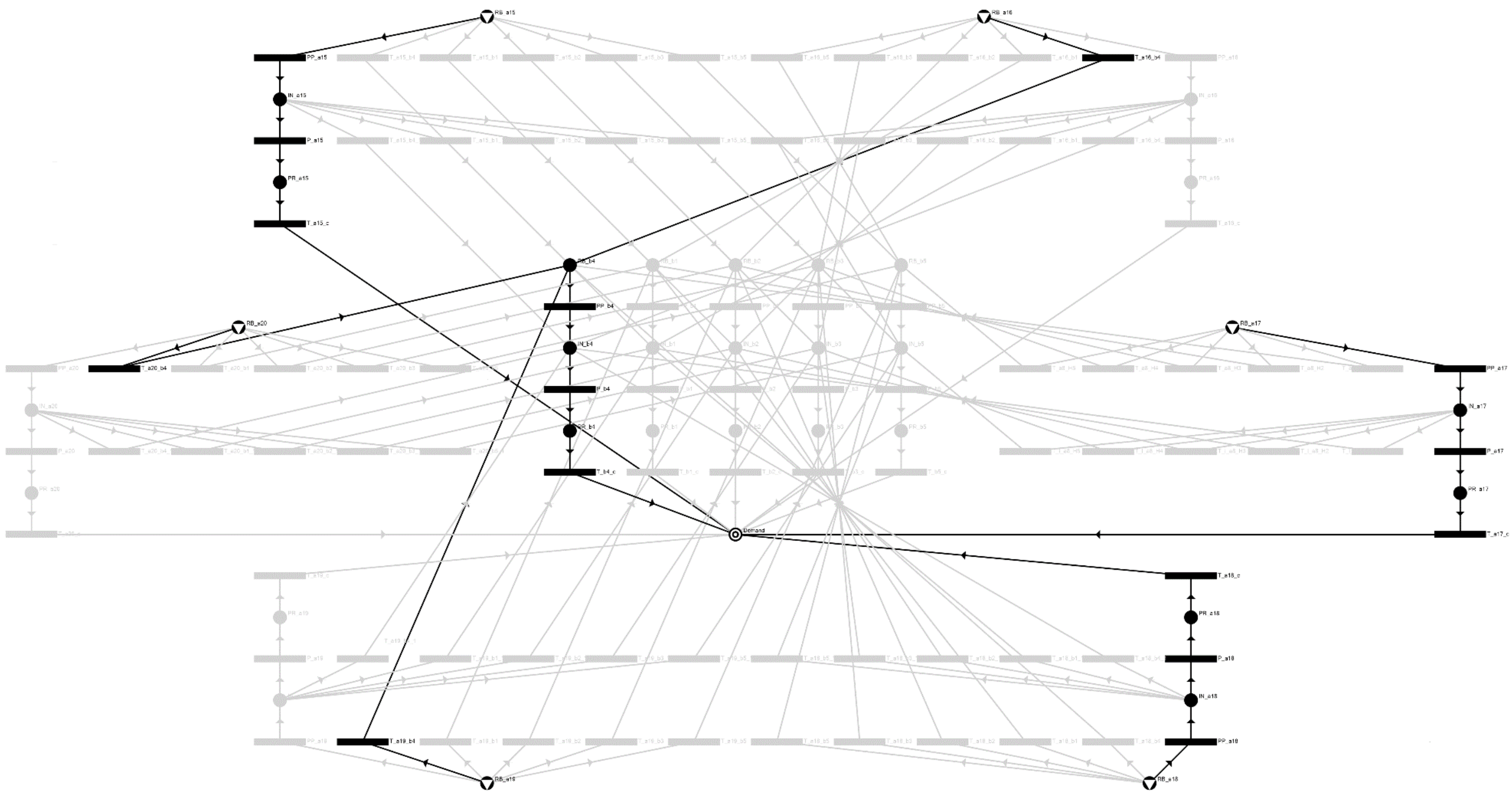

Figure A-8: Optimum structure for palm oil biomass supply chain with multiple hubs

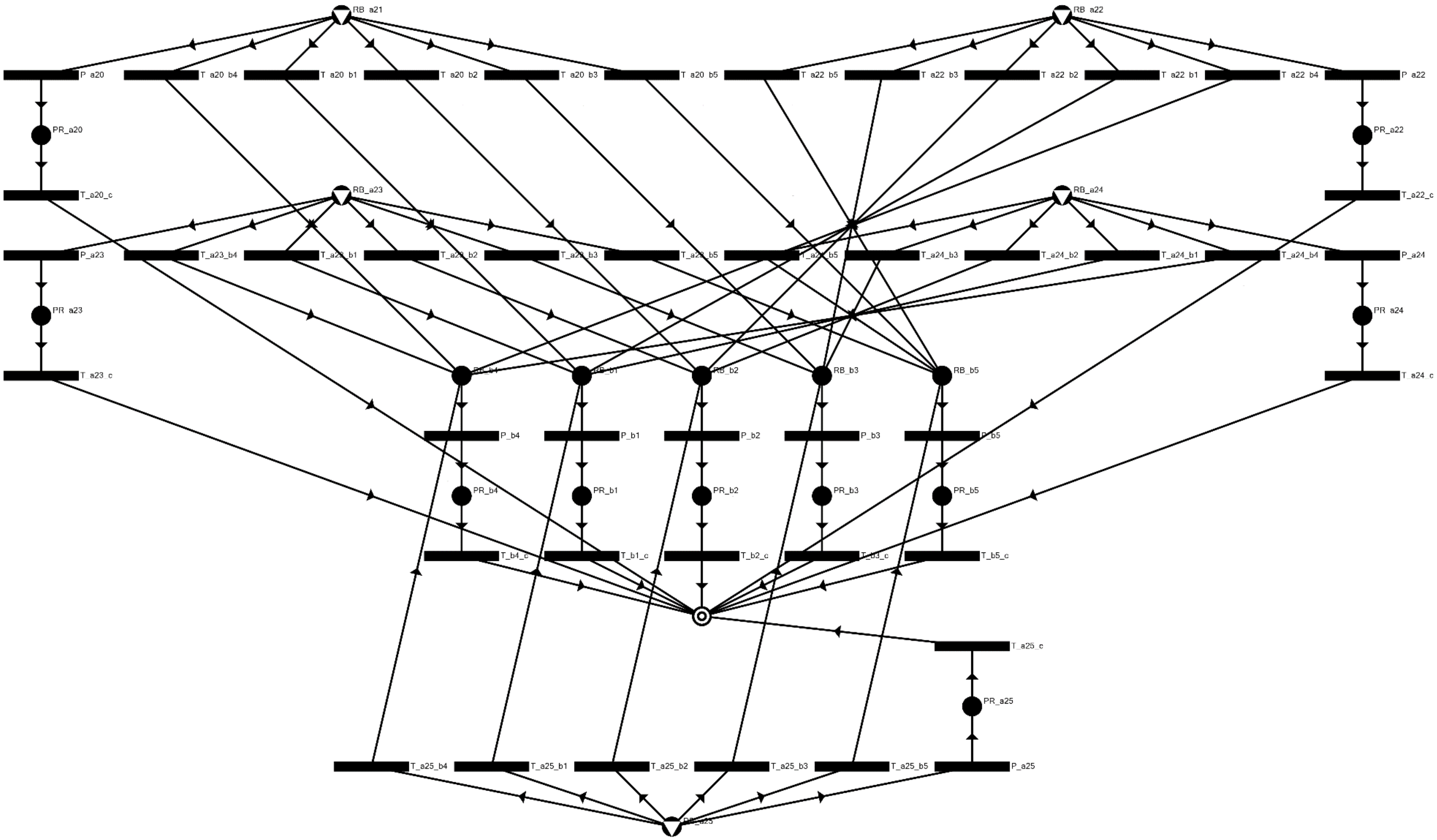

Figure A-9: Maximum structure for paddy biomass supply chain with multiple hubs

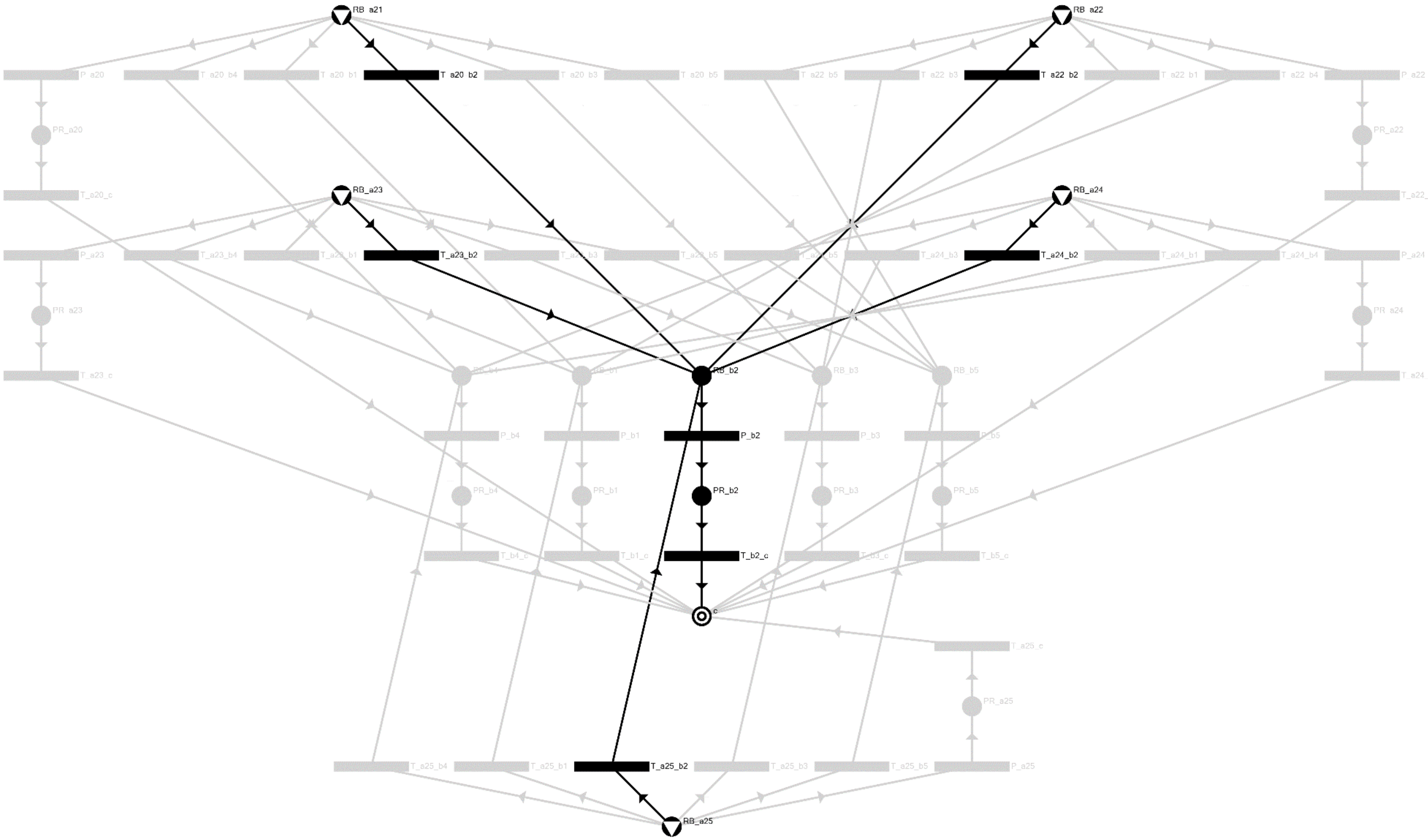

Figure A-10: Optimum structure for paddy biomass supply chain with multiple hubs

APPENDICES C

CHAPTER 6 SYNTHESIS OF BIOMASS SUPPLY CHAIN SYSTEM IN RURAL AND REMOTE REGION VIA RESOURCE INTEGRATED NETWORK (RIN)

C.1 Coding of Extended MBC

```
MODEL:

! Resource Integrated Network (RIN) - Extende Multiple Biomass Corridor
(MBC);

!Availability of bioresources d;
!d1=sago log, d2=fresh fruit brunches, d3=paddy, d4=keli fish, d5=egg;
d1=8800;
d2=11400;
d3=6700;
d4=2000;
d5=800;

!Amount of bioresources entering processing mill f;
!f1=sago starch production, f2=crude palm oil production, f3=rice
production,;
d1f1=d1;
d2f2=d2;
d3f3=d3;

!Given coversion of feedstock g from bioresources d via technology f;
!g1=sago starch, g2=sago fibre, g3=sago bark,
g4=crude palm oil, g5=empty fruit brunches, g6=palm kernel shell,
g7=rice, g8=rice husk, g9=rice straw;
f1g1=0.24;
f1g2=0.152;
f1g3=0.608;
f2g4=0.23;
f2g5=0.5467;
f2g6=0.2233;
f3g7=0.64;
f3g8=0.1548;
f3g9=0.2052;
!Amount of feedstock g produced from processing mill f;
g1=d1f1*f1g1;
g2=d1f1*f1g2;
g3=d1f1*f1g3;
g4=d2f2*f2g4;
g5=d2f2*f2g5;
g6=d2f2*f2g6;
```

```
g7=d3f3*f3g7;
g8=d3f3*f3g8;
g9=d3f3*f3g9;

!Amount of feedstock g flows into primary tecnology j;
!j1= Acid Fermentation, j2=alkaline fermentaion, j3= hot water fermentation,
j4 = steam fermentation, j5=gasification, j6=pyrolysis,
j7=Sieving and Separation, j8=briquetting, j9=boiler,;
g2=g2j1+g2j2+g2j3+g2j4+g2j5+g2j6;
g3=g3j1+g3j2+g3j3+g3j4+g3j5+g3j6;
g5=g5j7+g5j9;
g6=g6j8+g6j9+g6l1;
g8=g8j6;
g9=g9j9;

!Given conversion of intermediate k from feedstock g via technology j;
!k1=ethanol, k2=syngas, k3=bio-oil,
k4=wet short fibre, k5=wet long fibre, k6=briqutte,
k7=high pressure steam,;
j1k1g2=0.141;
j1k1g3=0.048;
j2k1g2=0.158;
j2k1g3=0.054;
j3k1g2=0.178;
j3k1g3=0.006;
j4k1g2=0.178;
j4k1g3=0.006;
j5k2g2=0.2271;
j5k2g3=0.222;
j6k3g2=0.32;
j6k3g3=0.32;
j6k3g8=0.63;
j7k4g6=0.24;
j7k5g6=0.67;
j8k6g6=0.33;
j8k6k4=0.33;
j9k7g5=2.59;
j9k7g6=3.95;
j9k7g9=3.83;

!Amount of intermediate k produced from tecnology j;
k1=
g2j1*j1k1g2+
g3j1*j1k1g3+
g2j2*j2k1g2+
g3j2*j2k1g3+
g2j3*j3k1g2+
g3j3*j3k1g3+
g2j4*j4k1g2+
g3j4*j4k1g3;
k2=
g2j5*j5k2g2+
g3j5*j5k2g3;
k3=
g2j6*j6k3g2+
g3j6*j6k3g3+
g8j6*j6k3g8;
```

```
k4=
g5j7*j7k4g6;
k5=
g5j7*j7k5g6;
k6=
g6j8*j8k6g6+
k4j8*j8k6k4;
k7=
g5j9*j9k7g5+
g6j9*j9k7g6+
g9j9*j9k7g9;

!Amount of intermediate k entering technology l;
!l1=pelletising, l2=drying, l3=steam engine;
k4=k4l1+k4j8;
k5=k5l2;
k7=k7l3;

!Given conversion of product m from intermediate k via technology l;
!m1=pellet, m2=dried long fibre, m3=electricity, m4=medium pressure steam;
l1m1k4=0.33;
l1m1g6=0.33;
l2m2k5=0.56;
l3m3k7=0.58;
l3m4k7=0.91;

!Amount of product m produced from technology j;
m1=k4l1*l1m1k4+g6l1*l1m1g6;
m2=k5l2*l2m2k5;
m3=k7l3*l3m3k7;
m4=k7l3*l3m4k7;

!Revenue r;
!Given price of the product;
cd4=1225;
cd5=2585;
cg1=390;
cg4=520;
cg7=400;
ck1=671;
ck2=198;
ck3=397;
ck6=120;
cm1=140;
cm2=160;
cm3=0.14;
cm4=6;
r=cd4*d4+cd5*5+cg1*g1+cg4*g4+cg7*g7+ck1*k1+ck2*k2+ck3*k3+ck6*k6+cm1*m1+cm2*m2
+cm3*m3+cm4*m4;

!Cost of production totcp;
!Given the cost of production of intermediate k via technology j or product m
via technology l
from respective feed stock g or intermediate k;
cpj1=98.1;
cpj2=94.6;
cpj3=70.5;
```

```
cpj4=63.5;
cpj5=43.8;
cpj6=277;
cpj8=46.1;
cpj9=2.6;
cpl1=52.2;
cpl2=58.3;
cpl3=0.05;
totcp=
cpj1*(g2j1*j1k1g2+g3j1*j1k1g3)+
cpj2*(g2j2*j2k1g2+g3j2*j2k1g3)+
cpj3*(g2j3*j3k1g2+g3j3*j3k1g3)+
cpj4*(g2j4*j4k1g2+g3j4*j4k1g3)+
cpj5*(g2j5*j5k2g2+g3j5*j5k2g3)+
cpj6*(g2j6*j6k3g2+g3j6*j6k3g3+g8j6*j6k3g8)+
cpj8*(g6j8*j8k6g6+k4j8*j8k6k4)+
cpj9*(g5j9*j9k7g5+g6j9*j9k7g6+g9j9*j9k7g9)+
cpl1*(k4l1*l1m1k4+g6l1*l1m1g6)+
cpl2*(k5l2*l2m2k5)+
cpl3*(k7l3*l3m3k7);


!Maximise objective function gross profit gp;
gp=r-totcp;
max=gp;

END
```

C.2 Result of Extended MBC

```
Global optimal solution found.
  Objective value:                              7163995.
  Infeasibilities:                              0.000000
  Total solver iterations:                             0
  Elapsed runtime seconds:                          0.03

  Model Class:                                        LP

  Total variables:                    35
  Nonlinear variables:                 0
  Integer variables:                   0

  Total constraints:                  22
  Nonlinear constraints:               0

  Total nonzeros:                     92
  Nonlinear nonzeros:                  0
```

Variable	Value	Reduced Cost
D1	8800.000	0.000000
D2	11400.00	0.000000
D3	6700.000	0.000000
D4	2000.000	0.000000
D5	800.0000	0.000000
D1F1	8800.000	0.000000
D2F2	11400.00	0.000000
D3F3	6700.000	0.000000
F1G1	0.2400000	0.000000
F1G2	0.1520000	0.000000
F1G3	0.6080000	0.000000
F2G4	0.2300000	0.000000
F2G5	0.5467000	0.000000
F2G6	0.2233000	0.000000
F3G7	0.6400000	0.000000
F3G8	0.1548000	0.000000
F3G9	0.2052000	0.000000
G1	2112.000	0.000000
G2	1337.600	0.000000
G3	5350.400	0.000000
G4	2622.000	0.000000
G5	6232.380	0.000000
G6	2545.620	0.000000
G7	4288.000	0.000000
G8	1037.160	0.000000
G9	1374.840	0.000000
G2J1	0.000000	27.35610
G2J2	0.000000	17.06380
G2J3	0.000000	1.246000
G2J4	1337.600	0.000000
G2J5	0.000000	73.11618

G2J6	0.000000	69.73500
G3J1	0.000000	10.90080
G3J2	0.000000	7.274400
G3J3	0.000000	34.79700
G3J4	0.000000	34.75500
G3J5	0.000000	4.167600
G3J6	5350.400	0.000000
G5J7	6232.380	0.000000
G5J9	0.000000	37.56900
G6J8	0.000000	4.587000
G6J9	0.000000	17.47081
G6L1	2545.620	0.000000
G8J6	1037.160	0.000000
G9J9	1374.840	0.000000
J1K1G2	0.1410000	0.000000
J1K1G3	0.4800000E-01	0.000000
J2K1G2	0.1580000	0.000000
J2K1G3	0.5400000E-01	0.000000
J3K1G2	0.1780000	0.000000
J3K1G3	0.6000000E-02	0.000000
J4K1G2	0.1780000	0.000000
J4K1G3	0.6000000E-02	0.000000
J5K2G2	0.2271000	0.000000
J5K2G3	0.2220000	0.000000
J6K3G2	0.3200000	0.000000
J6K3G3	0.3200000	0.000000
J6K3G8	0.6300000	0.000000
J7K4G6	0.2400000	0.000000
J7K5G6	0.6700000	0.000000
J8K6G6	0.3300000	0.000000
J8K6K4	0.3300000	0.000000
J9K7G5	2.590000	0.000000
J9K7G6	3.950000	0.000000
J9K7G9	3.830000	0.000000
K1	238.0928	0.000000
K2	0.000000	0.000000
K3	2365.539	0.000000
K4	1495.771	0.000000
K5	4175.695	0.000000
K6	0.000000	0.000000
K4J8	0.000000	4.587000
K7	5265.637	0.000000
K4L1	1495.771	0.000000
K5L2	4175.695	0.000000
K7L3	5265.637	0.000000
L1M1K4	0.3300000	0.000000
L1M1G6	0.3300000	0.000000
L2M2K5	0.5600000	0.000000
L3M3K7	0.5800000	0.000000
L3M4K7	0.9100000	0.000000
M1	1333.659	0.000000
M2	2338.389	0.000000
M3	3054.070	0.000000
M4	4791.730	0.000000
CD4	1225.000	0.000000
CD5	2585.000	0.000000
CG1	390.0000	0.000000

CG4	520.0000	0.000000
CG7	400.0000	0.000000
CK1	671.0000	0.000000
CK2	198.0000	0.000000
CK3	397.0000	0.000000
CK6	120.0000	0.000000
CM1	140.0000	0.000000
CM2	160.0000	0.000000
CM3	0.1400000	0.000000
CM4	6.000000	0.000000
R	8054157.	0.000000
CPJ1	98.10000	0.000000
CPJ2	94.60000	0.000000
CPJ3	70.50000	0.000000
CPJ4	63.50000	0.000000
CPJ5	43.80000	0.000000
CPJ6	277.0000	0.000000
CPJ8	46.10000	0.000000
CPJ9	2.600000	0.000000
CPL1	52.20000	0.000000
CPL2	58.30000	0.000000
CPL3	0.5000000E-01	0.000000
TOTCP	890161.6	0.000000
GP	7163995.	0.000000

C.3 Coding of VRP

```
MODEL:

!Resource Integrated Network (RIN) - Logistic Network via The Vehicle Routing
Problem (VRP);

SETS:
!Q(P) is the availability at village P,
      U(P) is the accumulated load at village P ;
  CITY/1..8/: S, U;
!DIST(P,Q) is the distance from village P to village Q,
      X(P,Q) is binary variable that denotes the selection of route.
      It is 1 if vehicle travels from city P to Q, else 0;
  CXC( CITY, CITY): DIST, X;
ENDSETS

DATA:
!Given the availability of village P, P1 is depot so availability is 0 ;
  S =
!Village,    P1     P2     P3     P4     P5     P6     P7     P8;
             0    4120   4270   4350   4520   4540   3960   3940;
!Distance from village P to village Q=Distance from village Q to village P;
  DIST =
!To Village,       P1     P2     P3     P4     P5     P6     P7     P8     From
Village;
                   0      12     7      5      10     18     16     11     !P1;
                   12     0      6      10     19     26     28     23     !P2;
                   7      6      0      9      18     25     18     18     !P3;
                   5      10     9      0      9      16     10     7      !P4;
                   10     19     18     9      0      7      4      4      !P5;
                   18     26     25     16     7      0      7      9      !P6;
                   16     28     18     7      4      9      0      5      !P6;
                   11     23     18     7      4      9      5      0;     !P7;
!Capacity of boat VCAP, annualised capital cost of boat ACCV,
 fuel consumption cost of boat FCV, nv is the number of trips;
  VCAP = 45000;
  ACCV = 500000;
  FCV = 1.6;
  nv = 200;
ENDDATA

!Total travel distance;
  D = @SUM( CXC: DIST * X);

! Let all x be binary variables;
  @FOR( CXC: @BIN( X));

!For each village, except depot....;
  @FOR( CITY( R)| R #GT# 1:

!A boat enter village R from village P;
  @SUM( CITY( P)| P #NE# R #AND# ( P #EQ# 1 #OR#
```

```
     S( P) + S( R) #LE# VCAP): X( P, R)) = 1;

!A boat exit village R to village Q;
  @SUM( CITY( Q)| Q #NE# R #AND# ( Q #EQ# 1 #OR#

     S( Q) + S( R) #LE# VCAP): X( R, Q)) = 1;

!A boat does not travel inside the same village;
  X( R, R) = 0;

!The cummulative load of boat is limited by its capacity VCAP;
  @BND( S( R), U( R), VCAP);

!Subtours elimination constraints;
!If K follows I, then can bound U( K) - U( I);
  @FOR( CITY( P)| P #NE# R #AND# P #NE# 1:
     U( R) >= U( P) + S( R) - VCAP + VCAP *
      ( X( R, P) + X( P, R)) - ( S( R) + S( P))
       * X( R, P););
!If K is 1st stop, then U( K) = Q( K);
  U( R) <= VCAP - ( VCAP - S( R)) * X( 1, R);
!If K is not 1st stop...;
  U( R)>= S( R)+ @SUM( CITY( P)|
     P #GT# 1: S( P) * X( P, R)););

!Number of boats needed, figure rounded up;
  VEHCLF = @SUM( CITY( P)| P #GT# 1: S( P))/ VCAP;
  VEHCLR = VEHCLF + 1.999 - @WRAP( VEHCLF - .001, 1);
  @SUM( CITY( Q)| Q #GT# 1: X( 1, Q)) >= VEHCLR;

!Total transportation cost ATR;
  ATR = VEHCLR*ACCV + nv*D*FCV;

!Objective Function;
  Min=D;

END
```

C.4 Result of VRP

```
Global optimal solution found.
  Objective value:                              59.00000
  Objective bound:                              59.00000
  Infeasibilities:                              0.000000
  Extended solver steps:                             140
  Total solver iterations:                          2739
  Elapsed runtime seconds:                          0.28

  Model Class:                                      MILP

  Total variables:                   67
  Nonlinear variables:                0
  Integer variables:                 57

  Total constraints:                 74
  Nonlinear constraints:              0

  Total nonzeros:                   396
  Nonlinear nonzeros:                 0
```

Variable	Value	Reduced Cost
VCAP	45000.00	0.000000
ACCV	500000.0	0.000000
FCV	1.600000	0.000000
NV	200.0000	0.000000
D	59.00000	0.000000
VEHCLF	0.6600000	0.000000
VEHCLR	1.000000	0.000000
ATR	518880.0	0.000000
S(1)	0.000000	0.000000
S(2)	4120.000	0.000000
S(3)	4270.000	0.000000
S(4)	4350.000	0.000000
S(5)	4520.000	0.000000
S(6)	4540.000	0.000000
S(7)	3960.000	0.000000
S(8)	3940.000	0.000000
U(1)	0.000000	0.000000
U(2)	25430.00	0.000000
U(3)	29700.00	0.000000
U(4)	21310.00	0.000000
U(5)	8460.000	0.000000
U(6)	13000.00	0.000000
U(7)	16960.00	0.000000
U(8)	3940.000	0.000000
DIST(1, 1)	0.000000	0.000000
DIST(1, 2)	12.00000	0.000000
DIST(1, 3)	7.000000	0.000000
DIST(1, 4)	5.000000	0.000000
DIST(1, 5)	10.00000	0.000000

```
DIST( 1, 6)        18.00000            0.000000
DIST( 1, 7)        16.00000            0.000000
DIST( 1, 8)        11.00000            0.000000
DIST( 2, 1)        12.00000            0.000000
DIST( 2, 2)        0.000000            0.000000
DIST( 2, 3)        6.000000            0.000000
DIST( 2, 4)        10.00000            0.000000
DIST( 2, 5)        19.00000            0.000000
DIST( 2, 6)        26.00000            0.000000
DIST( 2, 7)        28.00000            0.000000
DIST( 2, 8)        23.00000            0.000000
DIST( 3, 1)        7.000000            0.000000
DIST( 3, 2)        6.000000            0.000000
DIST( 3, 3)        0.000000            0.000000
DIST( 3, 4)        9.000000            0.000000
DIST( 3, 5)        18.00000            0.000000
DIST( 3, 6)        25.00000            0.000000
DIST( 3, 7)        18.00000            0.000000
DIST( 3, 8)        18.00000            0.000000
DIST( 4, 1)        5.000000            0.000000
DIST( 4, 2)        10.00000            0.000000
DIST( 4, 3)        9.000000            0.000000
DIST( 4, 4)        0.000000            0.000000
DIST( 4, 5)        9.000000            0.000000
DIST( 4, 6)        16.00000            0.000000
DIST( 4, 7)        10.00000            0.000000
DIST( 4, 8)        7.000000            0.000000
DIST( 5, 1)        10.00000            0.000000
DIST( 5, 2)        19.00000            0.000000
DIST( 5, 3)        18.00000            0.000000
DIST( 5, 4)        9.000000            0.000000
DIST( 5, 5)        0.000000            0.000000
DIST( 5, 6)        7.000000            0.000000
DIST( 5, 7)        4.000000            0.000000
DIST( 5, 8)        4.000000            0.000000
DIST( 6, 1)        18.00000            0.000000
DIST( 6, 2)        26.00000            0.000000
DIST( 6, 3)        25.00000            0.000000
DIST( 6, 4)        16.00000            0.000000
DIST( 6, 5)        7.000000            0.000000
DIST( 6, 6)        0.000000            0.000000
DIST( 6, 7)        7.000000            0.000000
DIST( 6, 8)        9.000000            0.000000
DIST( 7, 1)        16.00000            0.000000
DIST( 7, 2)        28.00000            0.000000
DIST( 7, 3)        18.00000            0.000000
DIST( 7, 4)        7.000000            0.000000
DIST( 7, 5)        4.000000            0.000000
DIST( 7, 6)        9.000000            0.000000
DIST( 7, 7)        0.000000            0.000000
DIST( 7, 8)        5.000000            0.000000
DIST( 8, 1)        11.00000            0.000000
DIST( 8, 2)        23.00000            0.000000
DIST( 8, 3)        18.00000            0.000000
DIST( 8, 4)        7.000000            0.000000
DIST( 8, 5)        4.000000            0.000000
DIST( 8, 6)        9.000000            0.000000
```

```
DIST( 8, 7)      5.000000      0.000000
DIST( 8, 8)      0.000000      0.000000
   X( 1, 1)      0.000000      0.000000
   X( 1, 2)      0.000000      12.00000
   X( 1, 3)      0.000000      7.000000
   X( 1, 4)      0.000000      5.000000
   X( 1, 5)      0.000000      10.00000
   X( 1, 6)      0.000000      18.00000
   X( 1, 7)      0.000000      16.00000
   X( 1, 8)      1.000000      11.00000
   X( 2, 1)      0.000000      12.00000
   X( 2, 2)      0.000000      0.000000
   X( 2, 3)      1.000000      6.000000
   X( 2, 4)      0.000000      10.00000
   X( 2, 5)      0.000000      19.00000
   X( 2, 6)      0.000000      26.00000
   X( 2, 7)      0.000000      28.00000
   X( 2, 8)      0.000000      23.00000
   X( 3, 1)      1.000000      7.000000
   X( 3, 2)      0.000000      6.000000
   X( 3, 3)      0.000000      0.000000
   X( 3, 4)      0.000000      9.000000
   X( 3, 5)      0.000000      18.00000
   X( 3, 6)      0.000000      25.00000
   X( 3, 7)      0.000000      18.00000
   X( 3, 8)      0.000000      18.00000
   X( 4, 1)      0.000000      5.000000
   X( 4, 2)      1.000000      10.00000
   X( 4, 3)      0.000000      9.000000
   X( 4, 4)      0.000000      0.000000
   X( 4, 5)      0.000000      9.000000
   X( 4, 6)      0.000000      16.00000
   X( 4, 7)      0.000000      10.00000
   X( 4, 8)      0.000000      7.000000
   X( 5, 1)      0.000000      10.00000
   X( 5, 2)      0.000000      19.00000
   X( 5, 3)      0.000000      18.00000
   X( 5, 4)      0.000000      9.000000
   X( 5, 5)      0.000000      0.000000
   X( 5, 6)      1.000000      7.000000
   X( 5, 7)      0.000000      4.000000
   X( 5, 8)      0.000000      4.000000
   X( 6, 1)      0.000000      18.00000
   X( 6, 2)      0.000000      26.00000
   X( 6, 3)      0.000000      25.00000
   X( 6, 4)      0.000000      16.00000
   X( 6, 5)      0.000000      7.000000
   X( 6, 6)      0.000000      0.000000
   X( 6, 7)      1.000000      7.000000
   X( 6, 8)      0.000000      9.000000
   X( 7, 1)      0.000000      16.00000
   X( 7, 2)      0.000000      28.00000
   X( 7, 3)      0.000000      18.00000
   X( 7, 4)      1.000000      7.000000
   X( 7, 5)      0.000000      4.000000
   X( 7, 6)      0.000000      9.000000
   X( 7, 7)      0.000000      0.000000
```

```
X( 7, 8)        0.000000        5.000000
X( 8, 1)        0.000000        11.00000
X( 8, 2)        0.000000        23.00000
X( 8, 3)        0.000000        18.00000
X( 8, 4)        0.000000        7.000000
X( 8, 5)        1.000000        4.000000
X( 8, 6)        0.000000        9.000000
X( 8, 7)        0.000000        5.000000
X( 8, 8)        0.000000        0.000000
```

APPENDICES D

CHAPTER 7 FUZZY ANALYTICAL NETWORK PROCESS (FANP) BASED SUSTAINABILITY ASSESSMENT FRAMEWORK FOR INTEGRATED BIOMASS SUPPLY CHAIN

D.1 Questionnaire

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Survey Participation Consent Form

Developing Sustainability Index as Assessment Tool for biomass supply chain with Fuzzy Analytic Network Process (FANP) Approach

Dear participant,

I invite you to participate in a research study entitled ***Developing Sustainability Index as Assessment Tool for biomass supply chain with Fuzzy Analytic Network Process (FANP) Approach***. I am currently enrolled in the PhD Program at University of Nottingham Malaysia Campus, and am in the process of writing my PhD thesis. The doctoral thesis is supervised by Professor DDr. Lam Hon Loong from University of Nottingham Malaysia Campus.

The human dependency on finite fossil fuel has led to its drastic depletion. Along with its detrimental effects on the environment, such practice is now deemed unsustainable. This phenomenon has led to the growth for utilisation of biomass in the production of biofuels and biochemicals. Efficient supply chain management is vital in ensuring the sustainability of the entire industry. Therefore, the purpose of the research is to develop sustainability index for the evaluation of supply chain performance. Sustainability indicators and composite index are increasingly recognized as a powerful tool for policy making and corporate communication in providing information on sustainability performance in areas such as environment, economic, and social.

Your participation in this research project is completely voluntary. You may decline altogether or leave blank any questions you don't wish to answer. There are no known risks to participation beyond those encountered in everyday life. Your responses will remain confidential and anonymous. No one other than the researchers will know your individual answers to this questionnaire. The results of the survey will be reported only in the aggregate format.

If you agree to participate in this research, please answer the questions on the questionnaire as best you can. It should take approximately 10 minutes in total to complete. Please return the questionnaire as soon as possible, ideally before 15th of January 2018.

If you have any questions about this research project or want a copy or summary of the study results, feel free to contact me at *016-9880356* or *kebx4hbi@nottingham.edu.my*. Your decision to complete and return this questionnaire will be interpreted as an indication of your consent to participate.

Thank you for your assistance in this important endeavour. I highly appreciate your contributions to this research project.

Regards,

HONG BOON HOOI

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Instruction

This questionnaire consists of 4 parts as the following:

Part I – To determine the responsibility of stakeholders with respect to sustainable development of biomass supply chain.

Part II – To determine the relationship of different sustainability indicator in deriving a comprehensive set of sustainability index.

Part III – To determine the dependence of sustainability indicators with respect to role of stakeholders.

Part IV – To determine the feedback dependence of stakeholders with respect to sustainability indicators.

Part V – To determine the inner-dependency relationship of industry stakeholders.

Please compare the pair of variables in the same row and indicate the level of dominance relationship (i.e. importance, likelihood, preference, influence, dependency) based on the scale of *equal, moderate, strong, very strong, and extreme*.

Part I

Based on the general biomass-to-bioproducts supply chain which **stakeholder** plays a more important role with respect to the **sustainable development** of the industry? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Stage	Level of importance					Stage
Government agency	Equally	Moderately	Strongly	Very strongly	Extremely	Industry players
Government agency	Equally	Moderately	Strongly	Very strongly	Extremely	Financier/ Investor
Government agency	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Industry players	Equally	Moderately	Strongly	Very strongly	Extremely	Financier/ Investor
Industry players	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Financier/ Investor	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher

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Part II

Which **sustainability indicators** play a more important role to encourage the adoption of **sustainable practices** in biomass industry? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Indicator	Level of importance					Indicator
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Carbon footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Water footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Water footprint
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Processing hub safety	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Processing hub safety	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Transportation safety	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation

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Part II

Which **sustainability indicators** play a more important role to encourage the adoption of **sustainable practices** in biomass industry? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Indicator	Level of importance					Indicator
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Carbon footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Water footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Water footprint
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Processing hub safety	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Processing hub safety	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Transportation safety	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation

2

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Part III

Which **sustainability indicators** play a more important role to encourage **government agency** to support the inclusion of sustainable practices in the biomass industry? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Indicator	Level of importance					Indicator
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Carbon footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Water footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Water footprint
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Processing hub safety	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Processing hub safety	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Transportation safety	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation

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Which **sustainability indicators** play a more important role to encourage **industry players** to include sustainable practices in their respective operation in the biomass industry? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Indicator	Level of importance					Indicator
Gross profit	Equally	Moderately	Strongly	**Very strongly**	Extremely	Carbon footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	**Extremely**	Water footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	**Extremely**	Land footprint
Gross profit	Equally	Moderately	**Strongly**	Very strongly	Extremely	Processing hub safety
Gross profit	Equally	Moderately	**Strongly**	Very strongly	Extremely	Transportation safety
Gross profit	Equally	Moderately	Strongly	Very strongly	**Extremely**	Job creation
Carbon footprint	Equally	**Moderately**	Strongly	Very strongly	Extremely	Water footprint
Carbon footprint	Equally	**Moderately**	Strongly	Very strongly	Extremely	Land footprint
Carbon footprint	Equally	**Moderately**	Strongly	Very strongly	Extremely	**Processing hub safety**
Carbon footprint	Equally	**Moderately**	Strongly	Very strongly	Extremely	**Transportation safety**
Carbon footprint	Equally	Moderately	**Strongly**	Very strongly	Extremely	Job creation
Water footprint	**Equally**	Moderately	Strongly	Very strongly	Extremely	Land footprint
Water footprint	Equally	Moderately	**Strongly**	Very strongly	Extremely	**Processing hub safety**
Water footprint	Equally	Moderately	**Strongly**	Very strongly	Extremely	**Transportation safety**
Water footprint	**Equally**	Moderately	Strongly	Very strongly	Extremely	Job creation
Land footprint	Equally	Moderately	**Strongly**	Very strongly	Extremely	**Processing hub safety**
Land footprint	Equally	Moderately	**Strongly**	Very strongly	Extremely	**Transportation safety**
Land footprint	**Equally**	Moderately	Strongly	Very strongly	Extremely	Job creation
Processing hub safety	**Equally**	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Processing hub safety	Equally	Moderately	**Strongly**	Very strongly	Extremely	Job creation
Transportation safety	Equally	Moderately	**Strongly**	Very strongly	Extremely	Job creation

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Which **sustainability indicators** play a more important role to encourage **financier/investor** to include sustainable practices in their financing decision for biomass industry? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Indicator	Level of importance					Indicator
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Carbon footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Water footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Water footprint
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Processing hub safety	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Processing hub safety	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Transportation safety	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation

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Which **sustainability indicators** play a more important role to encourage **researchers** to include sustainable practices in their research area to improve the biomass industry? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Indicator	Level of importance					Indicator
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Carbon footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Water footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Gross profit	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Water footprint
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Carbon footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Land footprint
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Water footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Processing hub safety
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Land footprint	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Processing hub safety	Equally	Moderately	Strongly	Very strongly	Extremely	Transportation safety
Processing hub safety	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation
Transportation safety	Equally	Moderately	Strongly	Very strongly	Extremely	Job creation

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Part IV

Which **stakeholders** play a more important role to ensure the **gross profit** of sustainable biomass supply chain? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Stakeholder	Level of importance					Stakeholder
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Industry player
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Investor	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher

Which **stakeholders** play a more important role to ensure the **carbon footprint** of sustainable biomass supply chain? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Stakeholder	Level of importance					Stakeholder
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Industry player
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Investor	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher

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Which **stakeholders** play a more important role to ensure the **water footprint** of sustainable biomass supply chain? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Stakeholder	Level of importance					Stakeholder
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Industry player
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Investor	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher

Which **stakeholders** play a more important role to ensure the **land footprint** of sustainable biomass supply chain? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Stakeholder	Level of importance					Stakeholder
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Industry player
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Investor	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher

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Which **stakeholders** play a more important role to ensure the **processing hub safety** of sustainable biomass supply chain? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Stakeholder	Level of importance					Stakeholder
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Industry player
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Investor	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher

Which **stakeholders** play a more important role to ensure the **transportation safety** of sustainable biomass supply chain? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Stakeholder	Level of importance					Stakeholder
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Industry player
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Investor	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher

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Which **stakeholders** play a more important role to ensure the **job creation** of sustainable biomass supply chain? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Stakeholder	Level of importance					Stakeholder
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Industry player
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Investor	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher

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Part V

Which **stakeholders** play a more important role to encourage **government agency** to support the inclusion of sustainable practices in the biomass industry? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Stakeholder	Level of importance					Stakeholder
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Investor	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher

Which **stakeholders** play a more important role to encourage **industry players** to include sustainable practices in their respective operation in the biomass industry? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Stakeholder	Level of importance					Stakeholder
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Investor	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher

Which **stakeholders** play a more important role to encourage **financier/investor** to include sustainable practices in their financing decision for biomass industry? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Stakeholder	Level of importance					Stakeholder
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Industry player
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Researcher

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Which **stakeholders** play a more important role to encourage **researchers** to include sustainable practices in their research area to improve the biomass industry? (i.e. *equally important, moderately more important, strongly more important, very strongly more important, extremely more important)*

Stakeholder	Level of importance					Stakeholder
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Industry player
Government	Equally	Moderately	Strongly	Very strongly	Extremely	Investor
Industry player	Equally	Moderately	Strongly	Very strongly	Extremely	Investor

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D.2 Pairwise Comparison

Pairwise comparison of **GOAL** to **Sustainability Indicators**

	Mode					Lower					Upper					
	Goal	S1	S2	S3	S4	Goal	S1	S2	S3	S4	Goal	S1	S2	S3	S4	PW
K1	S1	1.00	3.00	2.00	2.00	S1	1.00	1.50	1.20	1.20	S1	1.00	5.60	3.20	3.20	0.4761
	S2		1.00	0.50	0.50	S2		1.00	0.31	0.31	S2		1.00	0.83	0.83	0.1014
	S3			1.00	1.00	S3			1.00	1.00	S3			1.00	1.00	0.2483
	S4				1.00	S4				1.00	S4				1.00	0.1742
															λ	0.52028
	Goal	S1	S2	S3	S4	Goal	S1	S2	S3	S4	Goal	S1	S2	S3	S4	
K2	S1	1.00	5.00	3.00	2.00	S1	1.00	3.00	1.50	1.20	S1	1.00	7.90	5.60	3.20	
	S2		1.00	0.33	0.50	S2		1.00	0.18	0.31	S2		1.00	0.67	0.83	
	S3			1.00	2.00	S3			1.00	1.20	S3			1.00	3.20	
	S4				1.00	S4				1.00	S4				1.00	
	Goal	S1	S2	S3	S4	Goal	S1	S2	S3	S4	Goal	S1	S2	S3	S4	
K3	S1	1.00	3.00	3.00	2.00	S1	1.00	1.50	1.50	1.20	S1	1.00	5.60	5.60	3.20	
	S2		1.00	1.00	0.50	S2		1.00	1.00	0.31	S2		1.00	1.00	0.83	
	S3			1.00	2.00	S3			1.00	1.20	S3			1.00	3.20	
	S4				1.00	S4				1.00	S4				1.00	
	Goal	S1	S2	S3	S4	Goal	S1	S2	S3	S4	Goal	S1	S2	S3	S4	
K4	S1	1.00	5.00	2.00	3.00	S1	1.00	3.00	1.20	1.50	S1	1.00	7.90	3.20	5.60	
	S2		1.00	0.33	1.00	S2		1.00	0.18	1.00	S2		1.00	0.67	1.00	
	S3			1.00	2.00	S3			1.00	1.20	S3			1.00	3.20	
	S4				1.00	S4				1.00	S4				1.00	
	Goal	S1	S2	S3	S4	Goal	S1	S2	S3	S4	Goal	S1	S2	S3	S4	
Mean	S1	1.00	3.87	2.45	2.21	S1	1.00	2.12	1.34	1.27	S1	1.00	6.65	4.23	3.68	
	S2		1.00	0.49	0.59	S2		1.00	0.32	0.42	S2		1.00	0.78	0.87	
	S3			1.00	1.68	S3			1.00	1.15	S3			1.00	2.39	
	S4				1.00	S4				1.00	S4				1.00	

D.3 Coding of FANP

```
MODEL:

!FANP as assessment tool;

!fuzzy number triangular distribution (Lij, Mij, Uij) of judgement,
!upper right;

!Ratio Scale Estimation;
L12 = 2.12  ; M12 = 3.87      ; U12 = 6.65      ;
L13 = 1.34  ; M13 = 2.45      ; U13 = 4.23      ;
L14 = 1.27  ; M14 = 2.21      ; U14 = 3.68      ;


L23 = 0.32  ; M23 = 0.49      ; U23 = 0.78      ;
L24 = 0.42  ; M24 = 0.59      ; U24 = 0.87      ;

L34 = 1.15  ; M34 = 1.68      ; U34 = 2.39      ;

!lower left;

L21 = 1/U12 ; M21 = 1/M12     ; U21 = 1/L12     ;
L31 = 1/U13 ; M31 = 1/M13     ; U31 = 1/L13     ;
L41 = 1/U14 ; M41 = 1/M14     ; U41 = 1/L14     ;


L32 = 1/U23 ; M32 = 1/M23     ; U32 = 1/L23     ;
L42 = 1/U24 ; M42 = 1/M24     ; U42 = 1/L24     ;


L43 = 1/U34 ; M43 = 1/M34     ; U43 = 1/L34     ;


@free(lambda); !lambda for criteria;

max = lambda; !objective function
      !lambda greater than 0 means consistent judgement, otherwise,
inconsistent;

w1 + w2 + w3 + w4  = 1;
w1 >= 0;
w2 >= 0;
w3 >= 0;
w4 >= 0;


!upper right;
! 1-6;
(lambda)*(M12 - L12)*w2 - w1 + L12*w2 <= 0;
(lambda)*(U12 - M12)*w2 + w1 - U12*w2 <= 0;

(lambda)*(M13 - L13)*w3 - w1 + L13*w3 <= 0;
(lambda)*(U13 - M13)*w3 + w1 - U13*w3 <= 0;
```

```
(lambda)*(M14 - L14)*w4 - w1 + L14*w4 <= 0;
(lambda)*(U14 - M14)*w4 + w1 - U14*w4 <= 0;



!2-6;
(lambda)*(M23 - L23)*w3 - w2 + L23*w3 <= 0;
(lambda)*(U23 - M23)*w3 + w2 - U23*w3 <= 0;

(lambda)*(M24 - L24)*w4 - w2 + L24*w4 <= 0;
(lambda)*(U24 - M24)*w4 + w2 - U24*w4 <= 0;


!3-6;
(lambda)*(M34 - L34)*w4 - w3 + L34*w4 <= 0;
(lambda)*(U34 - M34)*w4 + w3 - U34*w4 <= 0;



!lower left;
!6-1;
(lambda)*(M21 - L21)*w1 - w2 + L21*w1 <= 0;
(lambda)*(U21 - M21)*w1 + w2 - U21*w1 <= 0;

(lambda)*(M31 - L31)*w1 - w3 + L31*w1 <= 0;
(lambda)*(U31 - M31)*w1 + w3 - U31*w1 <= 0;

(lambda)*(M41 - L41)*w1 - w4 + L41*w1 <= 0;
(lambda)*(U41 - M41)*w1 + w4 - U41*w1 <= 0;



!6-2;
(lambda)*(M32 - L32)*w2 - w3 + L32*w2 <= 0;
(lambda)*(U32 - M32)*w2 + w3 - U32*w2 <= 0;

(lambda)*(M42 - L42)*w2 - w4 + L42*w2 <= 0;
(lambda)*(U42 - M42)*w2 + w4 - U42*w2 <= 0;



!6-3;
(lambda)*(M43 - L43)*w3 - w4 + L43*w3 <= 0;
(lambda)*(U43 - M43)*w3 + w4 - U43*w3 <= 0;


A12 = w1/w2;
A13 = w1/w3;
A14 = w1/w4;
A23 = w2/w3;
A24 = w2/w4;
A34 = w3/w4;



END
```

D.4 Result of FANP

```
Local optimal solution found.
  Objective value:                              0.5202799
  Infeasibilities:                              0.4587969E-08
  Total solver iterations:                             23
  Elapsed runtime seconds:                           0.05

  Model Class:                                        NLP

  Total variables:                     11
  Nonlinear variables:                  5
  Integer variables:                    0

  Total constraints:                   36
  Nonlinear constraints:               30

  Total nonzeros:                      99
  Nonlinear nonzeros:                  60
```

Variable	Value	Reduced Cost
L12	2.120000	0.000000
M12	3.870000	0.000000
U12	6.650000	0.000000
L13	1.340000	0.000000
M13	2.450000	0.000000
U13	4.230000	0.000000
L14	1.270000	0.000000
M14	2.210000	0.000000
U14	3.680000	0.000000
L23	0.3200000	0.000000
M23	0.4900000	0.000000
U23	0.7800000	0.000000
L24	0.4200000	0.000000
M24	0.5900000	0.000000
U24	0.8700000	0.000000
L34	1.150000	0.000000
M34	1.680000	0.000000
U34	2.390000	0.000000
L21	0.1503759	0.000000
M21	0.2583979	0.000000
U21	0.4716981	0.000000
L31	0.2364066	0.000000
M31	0.4081633	0.000000
U31	0.7462687	0.000000
L41	0.2717391	0.000000
M41	0.4524887	0.000000
U41	0.7874016	0.000000
L32	1.282051	0.000000
M32	2.040816	0.000000
U32	3.125000	0.000000
L42	1.149425	0.000000

M42	1.694915	0.000000
U42	2.380952	0.000000
L43	0.4184100	0.000000
M43	0.5952381	0.000000
U43	0.8695652	0.000000
LAMBDA	0.5202799	0.000000
W1	0.4761229	0.000000
W2	0.1014186	0.000000
W3	0.2483026	0.000000
W4	0.1741560	0.000000
A12	4.694631	0.000000
A13	1.917511	0.000000
A14	2.733888	0.000000
A23	0.4084476	0.000000
A24	0.5823435	0.000000
A34	1.425748	0.000000

APPENDICES E

CHAPTER 8 FUZZY ANALYTICAL PROCESS NETWORK (FANP) AIDED MULTIPLE OBJECTIVES OPTIMISATION APPROACH FOR INTEGRATED BIOMASS SUPPLY CHAIN

E.1 Coding of MOO

```
MODEL:

!FANP MOO;

!Availability in Source A;
!Sugar cane;
a1s=1550; a2s=10; a3s=3550; a4s=50; a5s=460; a6s=270;
a7s=240; a8s=100; a9s=0; a10s=0; a11s=0; a12s=0;
!Pineapple;
a1pi=560; a2pi=0; a3pi=670; a4pi=320; a5pi=0; a6pi=1540;
a7pi=0; a8pi=170; a9pi=200; a10pi=0; a11pi=0; a12pi=0;
!Palm oil;
a1po=0; a2po=0; a3po=0; a4po=1174300; a5po=0; a6po=0;
a7po=939400; a8po=352200; a9po=0; a10po=1051400; a11po=469700; a12po=704500;
!Paddy;
a1p=2770; a2p=2610; a3p=1600; a4p=380; a5p=0; a6p=0;
a7p=0; a8p=0; a9p=0; a10p=350; a11p=0; a12p=0;
!Total biomass;
a1=a1s+a1pi+a1po+a1p;
a2=a2s+a2pi+a2po+a2p;
a3=a3s+a3pi+a3po+a3p;
a4=a4s+a4pi+a4po+a4p;
a5=a5s+a5pi+a5po+a5p;
a6=a6s+a6pi+a6po+a6p;
a7=a7s+a7pi+a7po+a7p;
a8=a8s+a8pi+a8po+a8p;
a9=a9s+a9pi+a9po+a9p;
a10=a10s+a10pi+a10po+a10p;
a11=a11s+a11pi+a11po+a11p;
a12=a12s+a12pi+a12po+a12p;


!Transfer from Source A to potential Hub B;
!5 potential hubs b1 b2 b3 b4 b5;
a1>=a1b1+a1b2+a1b3+a1b4+a1b5;
a2>=a2b1+a2b2+a2b3+a2b4+a2b5;
a3>=a3b1+a3b2+a3b3+a3b4+a3b5;
```

```
a4>=a4b1+a4b2+a4b3+a4b4+a4b5;
a5>=a5b1+a5b2+a5b3+a5b4+a5b5;
a6>=a6b1+a6b2+a6b3+a6b4+a6b5;
a7>=a7b1+a7b2+a7b3+a7b4+a7b5;
a8>=a8b1+a8b2+a8b3+a8b4+a8b5;
a9>=a9b1+a9b2+a9b3+a9b4+a9b5;
a10>=a10b1+a10b2+a10b3+a10b4+a10b5;
a11>=a11b1+a11b2+a11b3+a11b4+a11b5;
a12>=a12b1+a12b2+a12b3+a12b4+a12b5;

!Capacity Constraint of Hub B;
a1b1+a2b1+a3b1+a4b1+a5b1+a6b1+a7b1+a8b1+a9b1+a10b1+a11b1+a12b1<=4750500;
a1b2+a2b2+a3b2+a4b2+a5b2+a6b2+a7b2+a8b2+a9b2+a10b2+a11b2+a12b2<=5530800;
a1b3+a2b3+a3b3+a4b3+a5b3+a6b3+a7b3+a8b3+a9b3+a10b3+a11b3+a12b3<=4832000;
a1b4+a2b4+a3b4+a4b4+a5b4+a6b4+a7b4+a8b4+a9b4+a10b4+a11b4+a12b4<=5177000;
a1b5+a2b5+a3b5+a4b5+a5b5+a6b5+a7b5+a8b5+a9b5+a10b5+a11b5+a12b5<=4950900;

!Hub selection;
k=a1+a2+a3+a4+a5+a6+a7+a8+a9+a10+a11+a12;
bi1*(k)>=a1b1+a2b1+a3b1+a4b1+a5b1+a6b1+a7b1+a8b1+a9b1+a10b1+a11b1+a12b1;
bi2*(k)>=a1b2+a2b2+a3b2+a4b2+a5b2+a6b2+a7b2+a8b2+a9b2+a10b2+a11b2+a12b2;
bi3*(k)>=a1b3+a2b3+a3b3+a4b3+a5b3+a6b3+a7b3+a8b3+a9b3+a10b3+a11b3+a12b3;
bi4*(k)>=a1b4+a2b4+a3b4+a4b4+a5b4+a6b4+a7b4+a8b4+a9b4+a10b4+a11b4+a12b4;
bi5*(k)>=a1b5+a2b5+a3b5+a4b5+a5b5+a6b5+a7b5+a8b5+a9b5+a10b5+a11b5+a12b5;
!Number of hub required;
bi1+bi2+bi3+bi4+bi5>=0;
!Binary to denote selection of particular hub;
@bin(bi1);
@bin(bi2);
@bin(bi3);
@bin(bi4);
@bin(bi5);

!Distance from source A to Hub B;
!b1;
da1b1=199;
da2b1=5;
da3b1=193;
da4b1=86;
da5b1=129;
da6b1=211;
da7b1=132;
da8b1=90;
da9b1=170;
da10b1=140;
da11b1=107;
da12b1=135;
!b2;
da1b2=95;
da2b2=109;
da3b2=89;
da4b2=24;
da5b2=86;
da6b2=93;
da7b2=63;
da8b2=115;
da9b2=75;
```

```
da10b2=33;
da11b2=32;
da12b2=72;
!b3;
da1b3=112;
da2b3=119;
da3b3=106;
da4b3=34;
da5b3=65;
da6b3=110;
da7b3=44;
da8b3=96;
da9b3=48;
da10b3=52;
da11b3=13;
da12b3=53;
!b4;
da1b4=152;
da2b4=134;
da3b4=146;
da4b4=82;
da5b4=30;
da6b4=149;
da7b4=5;
da8b4=43;
da9b4=38;
da10b4=94;
da11b4=55;
da12b4=10;
!b5;
da1b5=192;
da2b5=134;
da3b5=186;
da4b5=121;
da5b5=22;
da6b5=189;
da7b5=44;
da8b5=76;
da9b5=68;
da10b5=134;
da11b5=95;
da12b5=37;

!Logistic cost from source A to hub B;
LCab=(a1b1)*(0.2*(da1b1)+0.5)+(a2b1)*(0.2*(da2b1)+0.5)+
(a3b1)*(0.2*(da3b1)+0.5)+(a4b1)*(0.2*(da4b1)+0.5)+
(a5b1)*(0.2*(da5b1)+0.5)+(a6b1)*(0.2*(da6b1)+0.5)+
(a7b1)*(0.2*(da7b1)+0.5)+(a8b1)*(0.2*(da8b1)+0.5)+
(a9b1)*(0.2*(da9b1)+0.5)+(a10b1)*(0.2*(da10b1)+0.5)+
(a11b1)*(0.2*(da11b1)+0.5)+(a12b1)*(0.2*(da12b1)+0.5)+
(a1b2)*(0.2*(da1b2)+0.5)+(a2b2)*(0.2*(da2b2)+0.5)+
(a3b2)*(0.2*(da3b2)+0.5)+(a4b2)*(0.2*(da4b2)+0.5)+
(a5b2)*(0.2*(da5b2)+0.5)+(a6b2)*(0.2*(da6b2)+0.5)+
(a7b2)*(0.2*(da7b2)+0.5)+(a8b2)*(0.2*(da8b2)+0.5)+
(a9b2)*(0.2*(da9b2)+0.5)+(a10b2)*(0.2*(da10b2)+0.5)+
(a11b2)*(0.2*(da11b2)+0.5)+(a12b2)*(0.2*(da12b2)+0.5)+
(a1b3)*(0.2*(da1b3)+0.5)+(a2b3)*(0.2*(da2b3)+0.5)+
```

```
(a3b3)*(0.2*(da3b3)+0.5)+(a4b3)*(0.2*(da4b3)+0.5)+
(a5b3)*(0.2*(da5b3)+0.5)+(a6b3)*(0.2*(da6b3)+0.5)+
(a7b3)*(0.2*(da7b3)+0.5)+(a8b3)*(0.2*(da8b3)+0.5)+
(a9b3)*(0.2*(da9b3)+0.5)+(a10b3)*(0.2*(da10b3)+0.5)+
(a11b3)*(0.2*(da11b3)+0.5)+(a12b3)*(0.2*(da12b3)+0.5)+
(a1b4)*(0.2*(da1b4)+0.5)+(a2b4)*(0.2*(da2b4)+0.5)+
(a3b4)*(0.2*(da3b4)+0.5)+(a4b4)*(0.2*(da4b4)+0.5)+
(a5b4)*(0.2*(da5b4)+0.5)+(a6b4)*(0.2*(da6b4)+0.5)+
(a7b4)*(0.2*(da7b4)+0.5)+(a8b4)*(0.2*(da8b4)+0.5)+
(a9b4)*(0.2*(da9b4)+0.5)+(a10b4)*(0.2*(da10b4)+0.5)+
(a11b4)*(0.2*(da11b4)+0.5)+(a12b4)*(0.2*(da12b4)+0.5)+
(a1b5)*(0.2*(da1b5)+0.5)+(a2b5)*(0.2*(da2b5)+0.5)+
(a3b5)*(0.2*(da3b5)+0.5)+(a4b5)*(0.2*(da4b5)+0.5)+
(a5b5)*(0.2*(da5b5)+0.5)+(a6b5)*(0.2*(da6b5)+0.5)+
(a7b5)*(0.2*(da7b5)+0.5)+(a8b5)*(0.2*(da8b5)+0.5)+
(a9b5)*(0.2*(da9b5)+0.5)+(a10b5)*(0.2*(da10b5)+0.5)+
(a11b5)*(0.2*(da11b5)+0.5)+(a12b5)*(0.2*(da12b5)+0.5);

!Availability in Hub B;
b1+b2+b3+b4+b5=k;
b1=a1b1+a2b1+a3b1+a4b1+a5b1+a6b1+a7b1+a8b1+a9b1+a10b1+a11b1+a12b1;
b2=a1b2+a2b2+a3b2+a4b2+a5b2+a6b2+a7b2+a8b2+a9b2+a10b2+a11b2+a12b2;
b3=a1b3+a2b3+a3b3+a4b3+a5b3+a6b3+a7b3+a8b3+a9b3+a10b3+a11b3+a12b3;
b4=a1b4+a2b4+a3b4+a4b4+a5b4+a6b4+a7b4+a8b4+a9b4+a10b4+a11b4+a12b4;
b5=a1b5+a2b5+a3b5+a4b5+a5b5+a6b5+a7b5+a8b5+a9b5+a10b5+a11b5+a12b5;

!Biomass type I in Hub B;
!Sugar cane consists of only bagasse i1;
!b1;
b1s=a1b1*(a1s/(a1s+a1pi+a1po+a1p))+a2b1*(a2s/(a2s+a2pi+a2po+a2p))+
a3b1*(a3s/(a3s+a3pi+a3po+a3p))+a4b1*(a4s/(a4s+a4pi+a4po+a4p))+
a5b1*(a5s/(a5s+a5pi+a5po+a5p))+a6b1*(a6s/(a6s+a6pi+a6po+a6p))+
a7b1*(a7s/(a7s+a7pi+a7po+a7p))+a8b1*(a8s/(a8s+a8pi+a8po+a8p))+
a8b1*(a9s/(a9s+a9pi+a9po+a9p))+a10b1*(a10s/(a10s+a10pi+a10po+a10p))+
a11b1*(a11s/(a11s+a11pi+a11po+a11p))+a12b1*(a12s/(a12s+a12pi+a12po+a12p));
b1i1=b1s;
!b2;
b2s=a1b2*(a1s/(a1s+a1pi+a1po+a1p))+a2b2*(a2s/(a2s+a2pi+a2po+a2p))+
a3b2*(a3s/(a3s+a3pi+a3po+a3p))+a4b2*(a4s/(a4s+a4pi+a4po+a4p))+
a5b2*(a5s/(a5s+a5pi+a5po+a5p))+a6b2*(a6s/(a6s+a6pi+a6po+a6p))+
a7b2*(a7s/(a7s+a7pi+a7po+a7p))+a8b2*(a8s/(a8s+a8pi+a8po+a8p))+
a9b2*(a9s/(a9s+a9pi+a9po+a9p))+a10b2*(a10s/(a10s+a10pi+a10po+a10p))+
a11b2*(a11s/(a11s+a11pi+a11po+a11p))+a12b2*(a12s/(a12s+a12pi+a12po+a12p));
b2i1=b2s;
!b3;
b3s=a1b3*(a1s/(a1s+a1pi+a1po+a1p))+a2b3*(a2s/(a2s+a2pi+a2po+a2p))+
a3b3*(a3s/(a3s+a3pi+a3po+a3p))+a4b3*(a4s/(a4s+a4pi+a4po+a4p))+
a5b3*(a5s/(a5s+a5pi+a5po+a5p))+a6b3*(a6s/(a6s+a6pi+a6po+a6p))+
a7b3*(a7s/(a7s+a7pi+a7po+a7p))+a8b3*(a8s/(a8s+a8pi+a8po+a8p))+
a9b3*(a9s/(a9s+a9pi+a9po+a9p))+a10b3*(a10s/(a10s+a10pi+a10po+a10p))+
a11b3*(a11s/(a11s+a11pi+a11po+a11p))+a12b3*(a12s/(a12s+a12pi+a12po+a12p));
b3i1=b3s;
!b4;
b4s=a1b4*(a1s/(a1s+a1pi+a1po+a1p))+a2b4*(a2s/(a2s+a2pi+a2po+a2p))+
a3b4*(a3s/(a3s+a3pi+a3po+a3p))+a4b4*(a4s/(a4s+a4pi+a4po+a4p))+
a5b4*(a5s/(a5s+a5pi+a5po+a5p))+a6b4*(a6s/(a6s+a6pi+a6po+a6p))+
a7b4*(a7s/(a7s+a7pi+a7po+a7p))+a8b4*(a8s/(a8s+a8pi+a8po+a8p))+
```

```
a9b4*(a9s/(a9s+a9pi+a9po+a9p))+a10b4*(a10s/(a10s+a10pi+a10po+a10p))+
a11b4*(a11s/(a11s+a11pi+a11po+a11p))+a12b4*(a12s/(a12s+a12pi+a12po+a12p));
b4i1=b4s;
!b5;
b5s=a1b5*(a1s/(a1s+a1pi+a1po+a1p))+a2b5*(a2s/(a2s+a2pi+a2po+a2p))+
a3b5*(a3s/(a3s+a3pi+a3po+a3p))+a4b5*(a4s/(a4s+a4pi+a4po+a4p))+
a5b5*(a5s/(a5s+a5pi+a5po+a5p))+a6b5*(a6s/(a6s+a6pi+a6po+a6p))+
a7b5*(a7s/(a7s+a7pi+a7po+a7p))+a8b5*(a8s/(a8s+a8pi+a8po+a8p))+
a9b5*(a9s/(a9s+a9pi+a9po+a9p))+a10b5*(a10s/(a10s+a10pi+a10po+a10p))+
a11b5*(a11s/(a11s+a11pi+a11po+a11p))+a12b5*(a12s/(a12s+a12pi+a12po+a12p));
b5i1=b5s;

!Pineapple consists of  60% peel i2 and  40% molasses i3;
!b1;
b1pi=a1b1*(a1pi/(a1s+a1pi+a1po+a1p))+a2b1*(a2pi/(a2s+a2pi+a2po+a2p))+
a3b1*(a3pi/(a3s+a3pi+a3po+a3p))+a4b1*(a4pi/(a4s+a4pi+a4po+a4p))+
a5b1*(a5pi/(a5s+a5pi+a5po+a5p))+a6b1*(a6pi/(a6s+a6pi+a6po+a6p))+
a7b1*(a7pi/(a7s+a7pi+a7po+a7p))+a8b1*(a8pi/(a8s+a8pi+a8po+a8p))+
a9b1*(a9pi/(a9s+a9pi+a9po+a9p))+a10b1*(a10pi/(a10s+a10pi+a10po+a10p))+
a11b1*(a11pi/(a11s+a11pi+a11po+a11p))+a12b1*(a12pi/(a12s+a12pi+a12po+a12p));
b1i2=b1pi*0.6;
b1i3=b1pi*0.4;
!b2;
b2pi=a1b2*(a1pi/(a1s+a1pi+a1po+a1p))+a2b2*(a2pi/(a2s+a2pi+a2po+a2p))+
a3b2*(a3pi/(a3s+a3pi+a3po+a3p))+a4b2*(a4pi/(a4s+a4pi+a4po+a4p))+
a5b2*(a5pi/(a5s+a5pi+a5po+a5p))+a6b2*(a6pi/(a6s+a6pi+a6po+a6p))+
a7b2*(a7pi/(a7s+a7pi+a7po+a7p))+a8b2*(a8pi/(a8s+a8pi+a8po+a8p))+
a9b2*(a9pi/(a9s+a9pi+a9po+a9p))+a10b2*(a10pi/(a10s+a10pi+a10po+a10p))+
a11b2*(a11pi/(a11s+a11pi+a11po+a11p))+a12b2*(a12pi/(a12s+a12pi+a12po+a12p));
b2i2=b2pi*0.6;
b2i3=b2pi*0.4;
!b3;
b3pi=a1b3*(a1pi/(a1s+a1pi+a1po+a1p))+a2b3*(a2pi/(a2s+a2pi+a2po+a2p))+
a3b3*(a3pi/(a3s+a3pi+a3po+a3p))+a4b3*(a4pi/(a4s+a4pi+a4po+a4p))+
a5b3*(a5pi/(a5s+a5pi+a5po+a5p))+a6b3*(a6pi/(a6s+a6pi+a6po+a6p))+
a7b3*(a7pi/(a7s+a7pi+a7po+a7p))+a8b3*(a8pi/(a8s+a8pi+a8po+a8p))+
a9b3*(a9pi/(a9s+a9pi+a9po+a9p))+a10b3*(a10pi/(a10s+a10pi+a10po+a10p))+
a11b3*(a11pi/(a11s+a11pi+a11po+a11p))+a12b3*(a12pi/(a12s+a12pi+a12po+a12p));
b3i2=b3pi*0.6;
b3i3=b3pi*0.4;
!b4;
b4pi=a1b4*(a1pi/(a1s+a1pi+a1po+a1p))+a2b4*(a2pi/(a2s+a2pi+a2po+a2p))+
a3b4*(a3pi/(a3s+a3pi+a3po+a3p))+a4b4*(a4pi/(a4s+a4pi+a4po+a4p))+
a5b4*(a5pi/(a5s+a5pi+a5po+a5p))+a6b4*(a6pi/(a6s+a6pi+a6po+a6p))+
a7b4*(a7pi/(a7s+a7pi+a7po+a7p))+a8b4*(a8pi/(a8s+a8pi+a8po+a8p))+
a9b4*(a9pi/(a9s+a9pi+a9po+a9p))+a10b4*(a10pi/(a10s+a10pi+a10po+a10p))+
a11b4*(a11pi/(a11s+a11pi+a11po+a11p))+a12b4*(a12pi/(a12s+a12pi+a12po+a12p));
b4i2=b4pi*0.6;
b4i3=b4pi*0.4;
!b5;
b5pi=a1b5*(a1pi/(a1s+a1pi+a1po+a1p))+a2b5*(a2pi/(a2s+a2pi+a2po+a2p))+
a3b5*(a3pi/(a3s+a3pi+a3po+a3p))+a4b5*(a4pi/(a4s+a4pi+a4po+a4p))+
a5b5*(a5pi/(a5s+a5pi+a5po+a5p))+a6b5*(a6pi/(a6s+a6pi+a6po+a6p))+
a7b5*(a7pi/(a7s+a7pi+a7po+a7p))+a8b5*(a8pi/(a8s+a8pi+a8po+a8p))+
a9b5*(a9pi/(a9s+a9pi+a9po+a9p))+a10b5*(a10pi/(a10s+a10pi+a10po+a10p))+
a11b5*(a11pi/(a11s+a11pi+a11po+a11p))+a12b5*(a12pi/(a12s+a12pi+a12po+a12p));
b5i2=b5pi*0.6;
```

```
b5i3=b5pi*0.4;

!Palm oil consists of 71% EFB i4 and 29% PKS i5;
!b1;
b1po=a1b1*(a1po/(a1s+a1pi+a1po+a1p))+a2b1*(a2po/(a2s+a2pi+a2po+a2p))+
a3b1*(a3po/(a3s+a3pi+a3po+a3p))+a4b1*(a4po/(a4s+a4pi+a4po+a4p))+
a5b1*(a5po/(a5s+a5pi+a5po+a5p))+a6b1*(a6po/(a6s+a6pi+a6po+a6p))+
a7b1*(a7po/(a7s+a7pi+a7po+a7p))+a8b1*(a8po/(a8s+a8pi+a8po+a8p))+
a9b1*(a9po/(a9s+a9pi+a9po+a9p))+a10b1*(a10po/(a10s+a10pi+a10po+a10p))+
a11b1*(a11po/(a11s+a11pi+a11po+a11p))+a12b1*(a12po/(a12s+a12pi+a12po+a12p));
b1i4=b1po*0.71;
b1i5=b1po*0.29;
!b2;
b2po=a1b2*(a1po/(a1s+a1pi+a1po+a1p))+a2b2*(a2po/(a2s+a2pi+a2po+a2p))+
a3b2*(a3po/(a3s+a3pi+a3po+a3p))+a4b2*(a4po/(a4s+a4pi+a4po+a4p))+
a5b2*(a5po/(a5s+a5pi+a5po+a5p))+a6b2*(a6po/(a6s+a6pi+a6po+a6p))+
a7b2*(a7po/(a7s+a7pi+a7po+a7p))+a8b2*(a8po/(a8s+a8pi+a8po+a8p))+
a9b2*(a9po/(a9s+a9pi+a9po+a9p))+a10b2*(a10po/(a10s+a10pi+a10po+a10p))+
a11b2*(a11po/(a11s+a11pi+a11po+a11p))+a12b2*(a12po/(a12s+a12pi+a12po+a12p));
b2i4=b2po*0.71;
b2i5=b2po*0.29;
!b3;
b3po=a1b3*(a1po/(a1s+a1pi+a1po+a1p))+a2b3*(a2po/(a2s+a2pi+a2po+a2p))+
a3b3*(a3po/(a3s+a3pi+a3po+a3p))+a4b3*(a4po/(a4s+a4pi+a4po+a4p))+
a5b3*(a5po/(a5s+a5pi+a5po+a5p))+a6b3*(a6po/(a6s+a6pi+a6po+a6p))+
a7b3*(a7po/(a7s+a7pi+a7po+a7p))+a8b3*(a8po/(a8s+a8pi+a8po+a8p))+
a9b3*(a9po/(a9s+a9pi+a9po+a9p))+a10b3*(a10po/(a10s+a10pi+a10po+a10p))+
a11b3*(a11po/(a11s+a11pi+a11po+a11p))+a12b3*(a12po/(a12s+a12pi+a12po+a12p));
b3i4=b3po*0.71;
b3i5=b3po*0.29;
!b4;
b4po=a1b4*(a1po/(a1s+a1pi+a1po+a1p))+a2b4*(a2po/(a2s+a2pi+a2po+a2p))+
a3b4*(a3po/(a3s+a3pi+a3po+a3p))+a4b4*(a4po/(a4s+a4pi+a4po+a4p))+
a5b4*(a5po/(a5s+a5pi+a5po+a5p))+a6b4*(a6po/(a6s+a6pi+a6po+a6p))+
a7b4*(a7po/(a7s+a7pi+a7po+a7p))+a8b4*(a8po/(a8s+a8pi+a8po+a8p))+
a9b4*(a9po/(a9s+a9pi+a9po+a9p))+a10b4*(a10po/(a10s+a10pi+a10po+a10p))+
a11b4*(a11po/(a11s+a11pi+a11po+a11p))+a12b4*(a12po/(a12s+a12pi+a12po+a12p));
b4i4=b4po*0.71;
b4i5=b4po*0.29;
!b5;
b5po=a1b5*(a1po/(a1s+a1pi+a1po+a1p))+a2b5*(a2po/(a2s+a2pi+a2po+a2p))+
a3b5*(a3po/(a3s+a3pi+a3po+a3p))+a4b5*(a4po/(a4s+a4pi+a4po+a4p))+
a5b5*(a5po/(a5s+a5pi+a5po+a5p))+a6b5*(a6po/(a6s+a6pi+a6po+a6p))+
a7b5*(a7po/(a7s+a7pi+a7po+a7p))+a8b5*(a8po/(a8s+a8pi+a8po+a8p))+
a9b5*(a9po/(a9s+a9pi+a9po+a9p))+a10b5*(a10po/(a10s+a10pi+a10po+a10p))+
a11b5*(a11po/(a11s+a11pi+a11po+a11p))+a12b5*(a12po/(a12s+a12pi+a12po+a12p));
b5i4=b5po*0.71;
b5i5=b5po*0.29;

!Paddy consists of 57% paddy straw i6 and 43% rice husk i7;
!b1;
b1p=a1b1*(a1p/(a1s+a1pi+a1po+a1p))+a2b1*(a2p/(a2s+a2pi+a2po+a2p))+
a3b1*(a3p/(a3s+a3pi+a3po+a3p))+a4b1*(a4p/(a4s+a4pi+a4po+a4p))+
a5b1*(a5p/(a5s+a5pi+a5po+a5p))+a6b1*(a6p/(a6s+a6pi+a6po+a6p))+
a7b1*(a7p/(a7s+a7pi+a7po+a7p))+a8b1*(a8p/(a8s+a8pi+a8po+a8p))+
a9b1*(a9p/(a9s+a9pi+a9po+a9p))+a10b1*(a10p/(a10s+a10pi+a10po+a10p))+
a11b1*(a11p/(a11s+a11pi+a11po+a11p))+a12b1*(a12p/(a12s+a12pi+a12po+a12p));
```

```
b1i6=b1p*0.57;
b1i7=b1p*0.43;
!b2;
b2p=a1b2*(a1p/(a1s+a1pi+a1po+a1p))+a2b2*(a2po/(a2s+a2pi+a2po+a2p))+
a3b2*(a3p/(a3s+a3pi+a3po+a3p))+a4b2*(a4p/(a4s+a4pi+a4po+a4p))+
a5b2*(a5p/(a5s+a5pi+a5po+a5p))+a6b2*(a6p/(a6s+a6pi+a6po+a6p))+
a7b2*(a7p/(a7s+a7pi+a7po+a7p))+a8b2*(a8p/(a8s+a8pi+a8po+a8p))+
a9b2*(a9p/(a9s+a9pi+a9po+a9p))+a10b2*(a10p/(a10s+a10pi+a10po+a10p))+
a11b2*(a11p/(a11s+a11pi+a11po+a11p))+a12b2*(a12p/(a12s+a12pi+a12po+a12p));
b2i6=b2p*0.57;
b2i7=b2p*0.43;
!b3;
b3p=a1b3*(a1p/(a1s+a1pi+a1po+a1p))+a2b3*(a2p/(a2s+a2pi+a2po+a2p))+
a3b3*(a3p/(a3s+a3pi+a3po+a3p))+a4b3*(a4p/(a4s+a4pi+a4po+a4p))+
a5b3*(a5p/(a5s+a5pi+a5po+a5p))+a6b3*(a6p/(a6s+a6pi+a6po+a6p))+
a7b3*(a7p/(a7s+a7pi+a7po+a7p))+a8b3*(a8p/(a8s+a8pi+a8po+a8p))+
a9b3*(a9p/(a9s+a9pi+a9po+a9p))+a10b3*(a10p/(a10s+a10pi+a10po+a10p))+
a11b3*(a11p/(a11s+a11pi+a11po+a11p))+a12b3*(a12p/(a12s+a12pi+a12po+a12p));
b3i6=b3p*0.57;
b3i7=b3p*0.43;
!b4;
b4p=a1b4*(a1p/(a1s+a1pi+a1po+a1p))+a2b4*(a2p/(a2s+a2pi+a2po+a2p))+
a3b4*(a3p/(a3s+a3pi+a3po+a3p))+a4b4*(a4p/(a4s+a4pi+a4po+a4p))+
a5b4*(a5p/(a5s+a5pi+a5po+a5p))+a6b4*(a6p/(a6s+a6pi+a6po+a6p))+
a7b4*(a7p/(a7s+a7pi+a7po+a7p))+a8b4*(a8p/(a8s+a8pi+a8po+a8p))+
a9b4*(a9p/(a9s+a9pi+a9po+a9p))+a10b4*(a10p/(a10s+a10pi+a10po+a10p))+
a11b4*(a11p/(a11s+a11pi+a11po+a11p))+a12b4*(a12p/(a12s+a12pi+a12po+a12p));
b4i6=b4p*0.57;
b4i7=b4p*0.43;
!b5;
b5p=a1b5*(a1p/(a1s+a1pi+a1po+a1p))+a2b5*(a2p/(a2s+a2pi+a2po+a2p))+
a3b5*(a3p/(a3s+a3pi+a3po+a3p))+a4b5*(a4p/(a4s+a4pi+a4po+a4p))+
a5b5*(a5p/(a5s+a5pi+a5po+a5p))+a6b5*(a6p/(a6s+a6pi+a6po+a6p))+
a7b5*(a7p/(a7s+a7pi+a7po+a7p))+a8b5*(a8p/(a8s+a8pi+a8po+a8p))+
a9b5*(a9p/(a9s+a9pi+a9po+a9p))+a10b5*(a10p/(a10s+a10pi+a10po+a10p))+
a11b5*(a11p/(a11s+a11pi+a11po+a11p))+a12b5*(a12p/(a12s+a12pi+a12po+a12p));
b5i6=b5p*0.57;
b5i7=b5p*0.43;

!Technology selection in Hub B;
!Layer i to j;
!j1=combustion, j2=separation and sieving, j3=palletising,
j4= briquetting, j5=acid fermentation, j6= alkaline fermenation,
j7=hot water fermentation, j8= steam fermentation, j9=solid fermentation,
j10=liquid fermentation, j11= anaerobic digestion, j12= fast pyrolyser,
j13= slow pyrolyser,;
!b1;
b1i1=b1i1j1+b1i1j5+b1i1j6+b1i1j7+b1i1j8;
b1i2=b1i2j9+b1i2j11;
b1i3=b1i2j10;
b1i4=b1i4j1+b1i4j2+b1i4j3+b1i4j4;
b1i5=b1i5j1+b1i5j3+b1i5j4;
b1i6=b1i6j1;
b1i7=b1i7j1+b1i7j12+b1i7j13;
!b2;
b2i1=b2i1j1+b2i1j5+b2i1j6+b2i1j7+b2i1j8;
b2i2=b2i2j9+b2i2j11;
```

```
b2i3=b2i2j10;
b2i4=b2i4j1+b2i4j2+b2i4j3+b2i4j4;
b2i5=b2i5j1+b2i5j3+b2i5j4;
b2i6=b2i6j1;
b2i7=b2i7j1+b2i7j12+b2i7j13;
!b3;
b3i1=b3i1j1+b3i1j5+b3i1j6+b3i1j7+b3i1j8;
b3i2=b3i2j9+b3i2j11;
b3i3=b3i2j10;
b3i4=b3i4j1+b3i4j2+b3i4j3+b3i4j4;
b3i5=b3i5j1+b3i5j3+b3i5j4;
b3i6=b3i6j1;
b3i7=b3i7j1+b3i7j12+b3i7j13;
!b4;
b4i1=b4i1j1+b4i1j5+b4i1j6+b4i1j7+b4i1j8;
b4i2=b4i2j9+b4i2j11;
b4i3=b4i2j10;
b4i4=b4i4j1+b4i4j2+b4i4j3+b4i4j4;
b4i5=b4i5j1+b4i5j3+b4i5j4;
b4i6=b4i6j1;
b4i7=b4i7j1+b4i7j12+b4i7j13;
!b5;
b5i1=b5i1j1+b5i1j5+b5i1j6+b5i1j7+b5i1j8;
b5i2=b5i2j9+b5i2j11;
b5i3=b5i2j10;
b5i4=b5i4j1+b5i4j2+b5i4j3+b5i4j4;
b5i5=b5i5j1+b5i5j3+b5i5j4;
b5i6=b5i6j1;
b5i7=b5i7j1+b5i7j12+b5i7j13;


!Layer j to k;
!k1=HPS, k2=WLF, k3=WSF, k4= pellete, k5=briqutte, k6=ethanol, k7=citric
acid,
k8=formic acid, k9=biogas, k10=biochar, k11=syngas, k12=pyoil;
!b1;
b1k1=b1i1j1*2.2+b1i4j1*2.59+b1i5j1*3.95+b1i6j1*3.83+b1i7j1*2.59;
b1k2=b1i4j2*0.67;
b1k3=b1i4j2*0.24;
b1k3=b1k3j3+b1k3j4;
b1k4=(b1i4j3+b1i5j3+b1k3j3)*0.33;
b1k5=(b1i4j4+b1i5j4+b1k3j4)*0.33;
b1k6=b1i1j5*252.62+b1i1j6*255.8+b1i1j7*255.27+b1i1j8*230.23;
b1k7=b1i2j9*0.9;
b1k8=b1i2j10*0.79;
b1k9=b1i2j11*500;
b1k10=b1i7j12*0.26+b1i7j13*0.36;
b1k11=b1i7j12*210+b1i7j13*640;
b1k12=b1i7j12*530;
!b2;
b2k1=b2i1j1*2.2+b2i4j1*2.59+b2i5j1*3.95+b2i6j1*3.83+b2i7j1*2.59;
b2k2=b2i4j2*0.67;
b2k3=b2i4j2*0.24;
b2k3=b2k3j3+b2k3j4;
b2k4=(b2i4j3+b2i5j3+b2k3j3)*0.33;
b2k5=(b2i4j4+b2i5j4+b2k3j4)*0.33;
```

```
b2k6=b2i1j5*252.62+b2i1j6*255.8+b2i1j7*255.27+b2i1j8*230.23;
b2k7=b2i2j9*0.9;
b2k8=b2i2j10*0.79;
b2k9=b2i2j11*500;
b2k10=b2i7j12*0.26+b2i7j13*0.36;
b2k11=b2i7j12*210+b2i7j13*640;
b2k12=b2i7j12*530;
!b3;
b3k1=b3i1j1*2.2+b3i4j1*2.59+b3i5j1*3.95+b3i6j1*3.83+b3i7j1*2.59;
b3k2=b3i4j2*0.67;
b3k3=b3i4j2*0.24;
b3k3=b3k3j3+b3k3j4;
b3k4=(b3i4j3+b3i5j3+b3k3j3)*0.33;
b3k5=(b3i4j4+b3i5j4+b3k3j4)*0.33;
b3k6=b3i1j5*252.62+b3i1j6*255.8+b3i1j7*255.27+b3i1j8*230.23;
b3k7=b3i2j9*0.9;
b3k8=b3i2j10*0.79;
b3k9=b3i2j11*500;
b3k10=b3i7j12*0.26+b3i7j13*0.36;
b3k11=b3i7j12*210+b3i7j13*640;
b3k12=b3i7j12*530;
!b4;
b4k1=b4i1j1*2.2+b4i4j1*2.59+b4i5j1*3.95+b4i6j1*3.83+b4i7j1*2.59;
b4k2=b4i4j2*0.67;
b4k3=b4i4j2*0.24;
b4k3=b4k3j3+b4k3j4;
b4k4=(b4i4j3+b4i5j3+b4k3j3)*0.33;
b4k5=(b4i4j4+b4i5j4+b4k3j4)*0.33;
b4k6=b4i1j5*252.62+b4i1j6*255.8+b4i1j7*255.27+b4i1j8*230.23;
b4k7=b4i2j9*0.9;
b4k8=b4i2j10*0.79;
b4k9=b4i2j11*500;
b4k10=b4i7j12*0.26+b4i7j13*0.36;
b4k11=b4i7j12*210+b4i7j13*640;
b4k12=b4i7j12*530;
!b5;
b5k1=b5i1j1*2.2+b5i4j1*2.59+b5i5j1*3.95+b5i6j1*3.83+b5i7j1*2.59;
b5k2=b5i4j2*0.67;
b5k3=b5i4j2*0.24;
b5k3=b5k3j3+b5k3j4;
b5k4=(b5i4j3+b5i5j3+b5k3j3)*0.33;
b5k5=(b5i4j4+b5i5j4+b5k3j4)*0.33;
b5k6=b5i1j5*252.62+b5i1j6*255.8+b5i1j7*255.27+b5i1j8*230.23;
b5k7=b5i2j9*0.9;
b5k8=b5i2j10*0.79;
b5k9=b5i2j11*500;
b5k10=b5i7j12*0.26+b5i7j13*0.36;
b5k11=b5i7j12*210+b5i7j13*640;
b5k12=b5i7j12*530;

!Layer k to l;
!l1=turbine, l2=drying, l3=waste oil injection;
!b1;
b1k1=b1k1l1;
b1k2=b1k2l2;
b1k5=b1k5l3;
```

```
b1k9=b1k9l1;
!b2;
b2k1=b2k1l1;
b2k2=b2k2l2;
b2k5=b2k5l3;
b2k9=b2k9l1;
!b3;
b3k1=b3k1l1;
b3k2=b3k2l2;
b3k5=b3k5l3;
b3k9=b3k9l1;
!b4;
b4k1=b4k1l1;
b4k2=b4k2l2;
b4k5=b4k5l3;
b4k9=b4k9l1;
!b5;
b5k1=b5k1l1;
b5k2=b5k2l2;
b5k5=b5k5l3;
b5k9=b5k9l1;

!Layer l to m;
!m1=electricity, m2=MPS, m3=DLF, m4=energy pack, wo=waste oil;
!b1;
b1m1=b1k1l1*0.58+b1k9l1*1.05;
b1m2=b1k1l1*0.91;
b1m3=b1k2l2*0.56;
b1m4=b1k5l3*1.15;

!b2;
b2m1=b2k1l1*0.58+b2k9l1*1.05;
b2m2=b2k1l1*0.91;
b2m3=b2k2l2*0.56;
b2m4=b2k5l3*1.15;

!b3;
b3m1=b3k1l1*0.58+b3k9l1*1.05;
b3m2=b3k1l1*0.91;
b3m3=b3k2l2*0.56;
b3m4=b3k5l3*1.15;

!b4;
b4m1=b4k1l1*0.58+b4k9l1*1.05;
b4m2=b4k1l1*0.91;
b4m3=b4k2l2*0.56;
b4m4=b4k5l3*1.15;

!b5;
b5m1=b5k1l1*0.58+b5k9l1*1.05;
b5m2=b5k1l1*0.91;
b5m3=b5k2l2*0.56;
b5m4=b5k5l3*1.15;
!Availability of engine oil;
(b1k5l3+b2k5l3+b3k5l3+b4k5l3+b5k5l3)/10000=20/3;
```

```
!Energy balance, er=electricity required, ei=import, ex=export,
sr=steam required, si=import, sx=export;
pe=0.000789;
!b1;
b1er=220*b1m3+b1k4*180+140*b1k5+b1m4*30+(141.467*b1i1j5*252.62*pe)+(133.016*b
1i1j6*255.8*pe)+(132.74*b1i1j7*255.27*pe)+
(133.53*b1i1j8*230.23*pe)+127*b1i2j9+b1i3j10*145+b1i2j11*120+90*b1i7j12+90*b1
i7j13;
b1er=b1m1+b1ei-b1ex;
b1sr=2.8*b1m3+3*b1k4+2.8*b1k5+(1.492*b1i1j5*252.62*pe)+(1.488*b1i1j6*255.8*pe
)+(1.534*b1i1j7*255.27*pe)+(0.928*b1i1j8*230.23*pe)+
0.63*b1i2j9+b1i3j10*0.1;
b1sr=b1m2+b1si-b1sx;
!b2;
b2er=220*b2m3+b2k4*180+140*b2k5+b2m4*30+(141.467*b2i1j5*252.62*pe)+(133.016*b
2i1j6*255.8*pe)+(132.74*b2i1j7*255.27*pe)+
(133.53*b2i1j8*230.23*pe)+127*b2i2j9+b2i3j10*145+b2i2j11*120+90*b2i7j12+90*b2
i7j13;
b2er=b2m1+b2ei-b2ex;
b2sr=2.8*b2m3+3*b2k4+2.8*b2k5+(1.492*b2i1j5*252.62*pe)+(1.488*b2i1j6*255.8*pe
)+(1.534*b2i1j7*255.27*pe)+(0.928*b2i1j8*230.23*pe)+
0.63*b2i2j9+b2i3j10*0.1;
b2sr=b2m2+b2si-b2sx;
!b3;
b3er=220*b3m3+b3k4*180+140*b3k5+b3m4*30+(141.467*b3i1j5*252.62*pe)+(133.016*b
3i1j6*255.8*pe)+(132.74*b3i1j7*255.27*pe)+
(133.53*b3i1j8*230.23*pe)+127*b3i2j9+b3i3j10*145+b3i2j11*120+90*b3i7j12+90*b3
i7j13;
b3er=b3m1+b3ei-b3ex;
b3sr=2.8*b3m3+3*b3k4+2.8*b3k5+(1.492*b3i1j5*252.62*pe)+(1.488*b3i1j6*255.8*pe
)+(1.534*b3i1j7*255.27*pe)+(0.928*b3i1j8*230.23*pe)+
0.63*b3i2j9+b3i3j10*0.1;
b3sr=b3m2+b3si-b3sx;
!b4;
b4er=220*b4m3+b4k4*180+140*b4k5+b4m4*30+(141.467*b4i1j5*252.62*pe)+(133.016*b
4i1j6*255.8*pe)+(132.74*b4i1j7*255.27*pe)+
(133.53*b4i1j8*230.23*pe)+127*b4i2j9+b4i3j10*145+b4i2j11*120+90*b4i7j12+90*b4
i7j13;
b4er=b4m1+b4ei-b4ex;
b4sr=2.8*b4m3+3*b4k4+2.8*b4k5+(1.492*b4i1j5*252.62*pe)+(1.488*b4i1j6*255.8*pe
)+(1.534*b4i1j7*255.27*pe)+(0.928*b4i1j8*230.23*pe)+
0.63*b4i2j9+b4i3j10*0.1;
b4sr=b4m2+b4si-b4sx;
!b5;
b5er=220*b5m3+b5k4*180+140*b5k5+b5m4*30+(141.467*b5i1j5*252.62*pe)+(133.016*b
5i1j6*255.8*pe)+(132.74*b5i1j7*255.27*pe)+
(133.53*b5i1j8*230.23*pe)+127*b5i2j9+b5i3j10*145+b5i2j11*120+90*b5i7j12+90*b5
i7j13;
b5er=b5m1+b5ei-b5ex;
b5sr=2.8*b5m3+3*b5k4+2.8*b5k5+(1.492*b5i1j5*252.62*pe)+(1.488*b5i1j6*255.8*pe
)+(1.534*b5i1j7*255.27*pe)+(0.928*b5i1j8*230.23*pe)+
0.63*b5i2j9+b5i3j10*0.1;
b5sr=b5m2+b5si-b5sx;
```

```
!Hub profit;
!b1;
!Capital cost of hub=10 million per year;
b1uc=0.14*b1ei+6*b1si;
b1cc=b1k1*2.6+0.1*b1m1+b1m3*27.5+b1k4*27+b1k5*26.5+12.5*b1m4+(69.723*b1i1j5*2
52.62*pe)+(67.091*b1i1j6*255.8*pe)+
(43.055*b1i1j7*255.27*pe)+(39.446*b1i1j8*230.23*pe)+217.3*b1i2j9+b1i3j10*178.
18+b1i2j11*69.4+200.867*b1i7j12+
66.833*b1i7j13;
b1pr=b1ex*0.11+4*b1sx+160*b1m3+b1k4*140+130*b1m4+0.53*b1k6+700*b1k7+b1k8*450+
350*b1k10+
0.122*b1k11+0.25*b1k12;
b1gp=b1pr-b1uc-b1cc-(bi1*10000000);
!b2;
b2uc=0.14*b2ei+6*b2si;
b2cc=b2k1*2.6+0.1*b2m1+b2m3*27.5+b2k4*27+b2k5*26.5+12.5*b2m4+(69.723*b2i1j5*2
52.62*pe)+(67.091*b2i1j6*255.8*pe)+
(43.055*b2i1j7*255.27*pe)+(39.446*b2i1j8*230.23*pe)+217.3*b2i2j9+b2i3j10*178.
18+b2i2j11*69.4+200.867*b2i7j12+
66.833*b2i7j13;
b2pr=b2ex*0.11+4*b2sx+160*b2m3+b2k4*140+130*b2m4+0.53*b2k6+700*b2k7+b2k8*450+
350*b2k10+
0.122*b2k11+0.25*b2k12;
b2gp=b2pr-b2uc-b2cc-(bi2*10000000);
!b3;
b3uc=0.14*b3ei+6*b3si;
b3cc=b3k1*2.6+0.1*b3m1+b3m3*27.5+b3k4*27+b3k5*26.5+12.5*b3m4+(69.723*b3i1j5*2
52.62*pe)+(67.091*b3i1j6*255.8*pe)+
(43.055*b3i1j7*255.27*pe)+(39.446*b3i1j8*230.23*pe)+217.3*b3i2j9+b3i3j10*178.
18+b3i2j11*69.4+200.867*b3i7j12+
66.833*b3i7j13;
b3pr=b3ex*0.11+4*b3sx+160*b3m3+b3k4*140+130*b3m4+0.53*b3k6+700*b3k7+b3k8*450+
350*b3k10+
0.122*b3k11+0.25*b3k12;
b3gp=b3pr-b3uc-b3cc-(bi3*10000000);
!b4;
b4uc=0.14*b4ei+6*b4si;
b4cc=b4k1*2.6+0.1*b4m1+b4m3*27.5+b4k4*27+b4k5*26.5+12.5*b4m4+(69.723*b4i1j5*2
52.62*pe)+(67.091*b4i1j6*255.8*pe)+
(43.055*b4i1j7*255.27*pe)+(39.446*b4i1j8*230.23*pe)+217.3*b4i2j9+b4i3j10*178.
18+b4i2j11*69.4+200.867*b4i7j12+
66.833*b4i7j13;
b4pr=b4ex*0.11+4*b4sx+160*b4m3+b4k4*140+130*b4m4+0.53*b4k6+700*b4k7+b4k8*450+
350*b4k10+
0.122*b4k11+0.25*b4k12;
b4gp=b4pr-b4uc-b4cc-(bi4*10000000);
!b5;
b5uc=0.14*b5ei+6*b5si;
b5cc=b5k1*2.6+0.1*b5m1+b5m3*27.5+b5k4*27+b5k5*26.5+12.5*b5m4+(69.723*b5i1j5*2
52.62*pe)+(67.091*b5i1j6*255.8*pe)+
(43.055*b5i1j7*255.27*pe)+(39.446*b5i1j8*230.23*pe)+217.3*b5i2j9+b5i3j10*178.
18+b5i2j11*69.4+200.867*b5i7j12+
66.833*b5i7j13;
b5pr=b5ex*0.11+4*b5sx+160*b5m3+b5k4*140+130*b5m4+0.53*b5k6+700*b5k7+b5k8*450+
350*b5k10+
0.122*b5k11+0.25*b5k12;
```

```
b5gp=b5pr-b5uc-b5cc-(bi5*10000000);

!From Processing hub B to demand C;
!c=johor port;
!b1;
b1c=b1k4+(b1k6*0.000789)++b1k7+b1k8+b1k10+(b1k11*0.00095)+b1m4+b1m3;
b2c=b2k4+(b2k6*0.000789)++b2k7+b2k8+b2k10+(b2k11*0.00095)+b2m4+b2m3;
b3c=b3k4+(b3k6*0.000789)+b3k7+b3k8+b3k10+(b3k11*0.00095)+b3m4+b3m3;
b4c=b4k4+(b4k6*0.000789)++b4k7+b4k8+b4k10+(b4k11*0.00095)+b4m4+b4m3;
b5c=b5k4+(b5k6*0.000789)++b5k7+b5k8+b5k10+(b5k11*0.00095)+b5m4+b5m3;

!Distance from hub B to demand C;
db1c=138.5;
db2c=105.4;
db3c=86.5;
db4c=65.6;
db5c=10;

!Logistic cost from hub B to demand C;
LCbc=b1c*(db1c*0.2+0.5)+b2c*(db2c*0.2+0.5)+b3c*(db3c*0.2+0.5)+b4c*(db4c*0.2+0
.5)+b5c*(db5c*0.2+0.5);

!Total logictic cost;
L=LCbc+LCab;

!Multiple Objective funtions;

!Gross Profit;
gp=(b3gp+b5gp+b2gp+b1gp+b4gp)-L;
!normalised;
gpn=(gp-28800000)/(78600000-28800000);

!Carbon Footprint;
!Process;
cfm3=0;
cfm4=0;
cfk1=0.159;
cfk4=0;
cfk7=0.03;
cfk8=0.035;
cfk9=0.097;
cfj12=0.041;
cfj13=0.046;
cfj5=0.113;
cfj6=0.121;
cfj7=0.115;
cfj8=0.087;
cfp= cfm3*(b1m3+b2m3+b3m3+b4m3+b5m3)+
cfm4*(b1m4+b2m4+b3m4+b4m4+b5m4)+
cfk4*(b1k4+b2k4+b3k4+b4k4+b5k4)+
cfk8*(b1k8+b2k8+b3k8+b4k8+b5k8)+
cfk7*(b1k7+b2k7+b3k7+b4k7+b5k7)+
cfk1*(b1k1l1+b2k1l1+b3k1l1+b4k1l1+b5k1l1)*0.58+
```

```
cfk9*(b1k9l1+b2k9l1+b3k9l1+b4k9l1+b5k9l1)*1.05+
cfj12*(b1i7j12+b2i7j12+b3i7j12+b4i7j12+b5i7j12)*0.26+
cfj13*(b1i7j13+b2i7j13+b3i7j13+b4i7j13+b5i7j13)*0.36+
cfj5*(b1i1j5*252.62+b2i1j5*252.62+b3i1j5*252.62+b4i1j5*252.62+b5i1j5*252.62)*
pe+
cfj6*(b1i1j6*255.8+b2i1j6*255.8+b3i1j6*255.8+b4i1j6*255.8+b5i1j6*255.8)*pe+
cfj7*(b1i1j7*255.27+b2i1j7*255.27+b3i1j7*255.27+b4i1j7*255.27+b5i1j7*255.27)*
pe+
cfj8*(b1i1j8*230.23+b2i1j8*230.23+b3i1j8*230.23+b4i1j8*230.23+b5i1j8*230.23)*
pe;
!Power;
efpc=0.8990;
cfpc=efpc*(b1ei+b2ei+b3ei+b4ei+b5ei);
!Fuel;
effc=0.092;
cffc=effc*((a1b1)*(da1b1)+(a2b1)*(da2b1)+
(a3b1)*(da3b1)+(a4b1)*(da4b1)+
(a5b1)*(da5b1)+(a6b1)*(da6b1)+
(a7b1)*(da7b1)+(a8b1)*(da8b1)+
(a9b1)*(da9b1)+(a10b1)*(da10b1)+
(a11b1)*(da11b1)+(a12b1)*(da12b1)+
(a1b2)*(da1b2)+(a2b2)*(da2b2)+
(a3b2)*(da3b2)+(a4b2)*(da4b2)+
(a5b2)*(da5b2)+(a6b2)*(da6b2)+
(a7b2)*(da7b2)+(a8b2)*(da8b2)+
(a9b2)*(da9b2)+(a10b2)*(da10b2)+
(a11b2)*(da11b2)+(a12b2)*(da12b2)+
(a1b3)*(da1b3)+(a2b3)*(da2b3)+
(a3b3)*(da3b3)+(a4b3)*(da4b3)+
(a5b3)*(da5b3)+(a6b3)*(da6b3)+
(a7b3)*(da7b3)+(a8b3)*(da8b3)+
(a9b3)*(da9b3)+(a10b3)*(da10b3)+
(a11b3)*(da11b3)+(a12b3)*(da12b3)+
(a1b4)*(da1b4)+(a2b4)*(da2b4)+
(a3b4)*(da3b4)+(a4b4)*(da4b4)+
(a5b4)*(da5b4)+(a6b4)*(da6b4)+
(a7b4)*(da7b4)+(a8b4)*(da8b4)+
(a9b4)*(da9b4)+(a10b4)*(da10b4)+
(a11b4)*(da11b4)+(a12b4)*(da12b4)+
(a1b5)*(da1b5)+(a2b5)*(da2b5)+
(a3b5)*(da3b5)+(a4b5)*(da4b5)+
(a5b5)*(da5b5)+(a6b5)*(da6b5)+
(a7b5)*(da7b5)+(a8b5)*(da8b5)+
(a9b5)*(da9b5)+(a10b5)*(da10b5)+
(a11b5)*(da11b5)+(a12b5)*(da12b5)+
b1c*db1c+b2c*db2c+b3c*db3c+b4c*db4c+b5c*db5c);
!Total;
cf=cfp+cfpc+cffc;
!Normalised;
cfn=(389000000-cf)/(389000000-298000000);

!Water Footprint;
!Process;
wfm3=0;
wfm4=0;
wfk1=0.022;
```

```
wfk4=0;
wfk7=0.021;
wfk8=0.026;
wfk9=0.017;
wfj12=0.023;
wfj13=0.023;
wfj5=0.149;
wfj6=0.151;
wfj7=0.169;
wfj8=0.115;
wfp= wfm3*(b1m3+b2m3+b3m3+b4m3+b5m3)+
wfm4*(b1m4+b2m4+b3m4+b4m4+b5m4)+
wfk4*(b1k4+b2k4+b3k4+b4k4+b5k4)+
wfk8*(b1k8+b2k8+b3k8+b4k8+b5k8)+
wfk7*(b1k7+b2k7+b3k7+b4k7+b5k7)+
wfk1*(b1k1l1+b2k1l1+b3k1l1+b4k1l1+b5k1l1)*0.58+
wfk9*(b1k9l1+b2k9l1+b3k9l1+b4k9l1+b5k9l1)*1.05+
wfj12*(b1i7j12+b2i7j12+b3i7j12+b4i7j12+b5i7j12)*0.26+
wfj13*(b1i7j13+b2i7j13+b3i7j13+b4i7j13+b5i7j13)*0.36+
wfj5*(b1i1j5*252.62+b2i1j5*252.62+b3i1j5*252.62+b4i1j5*252.62+b5i1j5*252.62)*
pe+
wfj6*(b1i1j6*255.8+b2i1j6*255.8+b3i1j6*255.8+b4i1j6*255.8+b5i1j6*255.8)*pe+
wfj7*(b1i1j7*255.27+b2i1j7*255.27+b3i1j7*255.27+b4i1j7*255.27+b5i1j7*255.27)*
pe+
wfj8*(b1i1j8*230.23+b2i1j8*230.23+b3i1j8*230.23+b4i1j8*230.23+b5i1j8*230.23)*
pe;
!Power;
wrpc=0.0022;
wfpc=wrpc*(b1ei+b2ei+b3ei+b4ei+b5ei);
!Fuel;
wrfc=0.024;
wffc=wrfc*((a1b1)*(da1b1)+(a2b1)*(da2b1)+
(a3b1)*(da3b1)+(a4b1)*(da4b1)+
(a5b1)*(da5b1)+(a6b1)*(da6b1)+
(a7b1)*(da7b1)+(a8b1)*(da8b1)+
(a9b1)*(da9b1)+(a10b1)*(da10b1)+
(a11b1)*(da11b1)+(a12b1)*(da12b1)+
(a1b2)*(da1b2)+(a2b2)*(da2b2)+
(a3b2)*(da3b2)+(a4b2)*(da4b2)+
(a5b2)*(da5b2)+(a6b2)*(da6b2)+
(a7b2)*(da7b2)+(a8b2)*(da8b2)+
(a9b2)*(da9b2)+(a10b2)*(da10b2)+
(a11b2)*(da11b2)+(a12b2)*(da12b2)+
(a1b3)*(da1b3)+(a2b3)*(da2b3)+
(a3b3)*(da3b3)+(a4b3)*(da4b3)+
(a5b3)*(da5b3)+(a6b3)*(da6b3)+
(a7b3)*(da7b3)+(a8b3)*(da8b3)+
(a9b3)*(da9b3)+(a10b3)*(da10b3)+
(a11b3)*(da11b3)+(a12b3)*(da12b3)+
(a1b4)*(da1b4)+(a2b4)*(da2b4)+
(a3b4)*(da3b4)+(a4b4)*(da4b4)+
(a5b4)*(da5b4)+(a6b4)*(da6b4)+
(a7b4)*(da7b4)+(a8b4)*(da8b4)+
(a9b4)*(da9b4)+(a10b4)*(da10b4)+
(a11b4)*(da11b4)+(a12b4)*(da12b4)+
(a1b5)*(da1b5)+(a2b5)*(da2b5)+
(a3b5)*(da3b5)+(a4b5)*(da4b5)+
```

```
(a5b5)*(da5b5)+(a6b5)*(da6b5)+
(a7b5)*(da7b5)+(a8b5)*(da8b5)+
(a9b5)*(da9b5)+(a10b5)*(da10b5)+
(a11b5)*(da11b5)+(a12b5)*(da12b5)+
b1c*db1c+b2c*db2c+b3c*db3c+b4c*db4c+b5c*db5c);
!Total;
wf=wfp+wfpc+wffc;
!normalised;
wfn=(10889840-wf)/(10889840-6134732);

!Land Footprint;
lrh=20000;
lrc=0.019;
lfh=(bi1+bi2+bi3+bi4+bi5)*lrh;
lfc=(b1c+b2c+b3c+b4c+b5c)*lrc;
!total;
lf=lfh+lfc;
!normalised;
lfn=(88089.17-lf)/(88089.17-48053.67);

!ISI;
isim3=12;
isim4=13;
isik1=35;
isik4=10;
isik7=25;
isik8=27;
isik9=30;
isij12=30;
isij13=31;
isij5=22;
isij6=22;
isij7=24;
isij8=26;
MV=10000000;
bim3*MV>=(b1m3+b2m3+b3m3+b4m3+b5m3);
bim4*MV>=(b1m4+b2m4+b3m4+b4m4+b5m4);
bik1*MV>=(b1k1l1+b2k1l1+b3k1l1+b4k1l1+b5k1l1);
bik4*MV>=(b1k4+b2k4+b3k4+b4k4+b5k4);
bik7*MV>=(b1k7+b2k7+b3k7+b4k7+b5k7);
bik8*MV>=(b1k8+b2k8+b3k8+b4k8+b5k8);
bik9*MV>=(b1k9l1+b2k9l1+b3k9l1+b4k9l1+b5k9l1);
bij12*MV>=(b1i7j12+b2i7j12+b3i7j12+b4i7j12+b5i7j12);
bij13*MV>=(b1i7j13+b2i7j13+b3i7j13+b4i7j13+b5i7j13);
bij5*MV>=(b1i1j5*252.62+b2i1j5*252.62+b3i1j5*252.62+b4i1j5*252.62+b5i1j5*252.
62)*pe;
bij6*MV>=(b1i1j6*255.8+b2i1j6*255.8+b3i1j6*255.8+b4i1j6*255.8+b5i1j6*255.8)*p
e;
bij7*MV>=(b1i1j7*255.27+b2i1j7*255.27+b3i1j7*255.27+b4i1j7*255.27+b5i1j7*255.
27)*pe;
bij8*MV>=(b1i1j8*230.23+b2i1j8*230.23+b3i1j8*230.23+b4i1j8*230.23+b5i1j8*230.
23)*pe;
@bin(bim3);@bin(bim4);@bin(bik1);@bin(bik4);@bin(bik7);@bin(bik9);@bin(bij12)
;@bin(bij13);@bin(bij5);@bin(bij6);
@bin(bij7);@bin(bij8);@bin(bik8);
!total;
```

```
ISI=bim3*isim3+bim4*isim4+bik1*isik1+bik4*isik4+bik7*isik7+bik8*isik8+bik9*is
ik9+bij12*isij12+bij13*isij13+
bij5*isij5+bij6*isij6+bij7*isij7+bij8*isij8;
!normalised;
isin=(180-isi)/(180-122);

!Death Risk;
ADR=0.049;
bia1b1*MV>=a1b1;@bin(bia1b1);
bia2b1*MV>=a2b1;@bin(bia2b1);
bia3b1*MV>=a3b1;@bin(bia3b1);
bia4b1*MV>=a4b1;@bin(bia4b1);
bia5b1*MV>=a5b1;@bin(bia5b1);
bia6b1*MV>=a6b1;@bin(bia6b1);
bia7b1*MV>=a7b1;@bin(bia7b1);
bia8b1*MV>=a8b1;@bin(bia8b1);
bia9b1*MV>=a9b1;@bin(bia9b1);
bia10b1*MV>=a10b1;@bin(bia10b1);
bia11b1*MV>=a11b1;@bin(bia11b1);
bia12b1*MV>=a12b1;@bin(bia12b1);
bia1b2*MV>=a1b2;@bin(bia1b2);
bia2b2*MV>=a2b2;@bin(bia2b2);
bia3b2*MV>=a3b2;@bin(bia3b2);
bia4b2*MV>=a4b2;@bin(bia4b2);
bia5b2*MV>=a5b2;@bin(bia5b2);
bia6b2*MV>=a6b2;@bin(bia6b2);
bia7b2*MV>=a7b2;@bin(bia7b2);
bia8b2*MV>=a8b2;@bin(bia8b2);
bia9b2*MV>=a9b2;@bin(bia9b2);
bia10b2*MV>=a10b2;@bin(bia10b2);
bia11b2*MV>=a11b2;@bin(bia11b2);
bia12b2*MV>=a12b2;@bin(bia12b2);
bia1b3*MV>=a1b3;@bin(bia1b3);
bia2b3*MV>=a2b3;@bin(bia2b3);
bia3b3*MV>=a3b3;@bin(bia3b3);
bia4b3*MV>=a4b3;@bin(bia4b3);
bia5b3*MV>=a5b3;@bin(bia5b3);
bia6b3*MV>=a6b3;@bin(bia6b3);
bia7b3*MV>=a7b3;@bin(bia7b3);
bia8b3*MV>=a8b3;@bin(bia8b3);
bia9b3*MV>=a9b3;@bin(bia9b3);
bia10b3*MV>=a10b3;@bin(bia10b3);
bia11b3*MV>=a11b3;@bin(bia11b3);
bia12b3*MV>=a12b3;@bin(bia12b3);
bia1b4*MV>=a1b4;@bin(bia1b4);
bia2b4*MV>=a2b4;@bin(bia2b4);
bia3b4*MV>=a3b4;@bin(bia3b4);
bia4b4*MV>=a4b4;@bin(bia4b4);
bia5b4*MV>=a5b4;@bin(bia5b4);
bia6b4*MV>=a6b4;@bin(bia6b4);
bia7b4*MV>=a7b4;@bin(bia7b4);
bia8b4*MV>=a8b4;@bin(bia8b4);
bia9b4*MV>=a9b4;@bin(bia9b4);
bia10b4*MV>=a10b4;@bin(bia10b4);
bia11b4*MV>=a11b4;@bin(bia11b4);
bia12b4*MV>=a12b4;@bin(bia12b4);
bia1b5*MV>=a1b5;@bin(bia1b5);
```

```
bia2b5*MV>=a2b5;@bin(bia2b5);
bia3b5*MV>=a3b5;@bin(bia3b5);
bia4b5*MV>=a4b5;@bin(bia4b5);
bia5b5*MV>=a5b5;@bin(bia5b5);
bia6b5*MV>=a6b5;@bin(bia6b5);
bia7b5*MV>=a7b5;@bin(bia7b5);
bia8b5*MV>=a8b5;@bin(bia8b5);
bia9b5*MV>=a9b5;@bin(bia9b5);
bia10b5*MV>=a10b5;@bin(bia10b5);
bia11b5*MV>=a11b5;@bin(bia11b5);
bia12b5*MV>=a12b5;@bin(bia12b5);
bib1c*MV>=b1c;@bin(bib1c);
bib2c*MV>=b2c;@bin(bib2c);
bib3c*MV>=b3c;@bin(bib3c);
bib4c*MV>=b4c;@bin(bib4c);
bib5c*MV>=b5c;@bin(bib5c);
DR=ADR*((bia1b1)*(da1b1)+(bia2b1)*(da2b1)+
(bia3b1)*(da3b1)+(bia4b1)*(da4b1)+
(bia5b1)*(da5b1)+(bia6b1)*(da6b1)+
(bia7b1)*(da7b1)+(bia8b1)*(da8b1)+
(bia9b1)*(da9b1)+(bia10b1)*(da10b1)+
(bia11b1)*(da11b1)+(bia12b1)*(da12b1)+
(bia1b2)*(da1b2)+(bia2b2)*(da2b2)+
(bia3b2)*(da3b2)+(bia4b2)*(da4b2)+
(bia5b2)*(da5b2)+(bia6b2)*(da6b2)+
(bia7b2)*(da7b2)+(bia8b2)*(da8b2)+
(bia9b2)*(da9b2)+(bia10b2)*(da10b2)+
(bia11b2)*(da11b2)+(bia12b2)*(da12b2)+
(bia1b3)*(da1b3)+(bia2b3)*(da2b3)+
(bia3b3)*(da3b3)+(bia4b3)*(da4b3)+
(bia5b3)*(da5b3)+(bia6b3)*(da6b3)+
(bia7b3)*(da7b3)+(bia8b3)*(da8b3)+
(bia9b3)*(da9b3)+(bia10b3)*(da10b3)+
(bia11b3)*(da11b3)+(bia12b3)*(da12b3)+
(bia1b4)*(da1b4)+(bia2b4)*(da2b4)+
(bia3b4)*(da3b4)+(bia4b4)*(da4b4)+
(bia5b4)*(da5b4)+(bia6b4)*(da6b4)+
(bia7b4)*(da7b4)+(bia8b4)*(da8b4)+
(bia9b4)*(da9b4)+(bia10b4)*(da10b4)+
(bia11b4)*(da11b4)+(bia12b4)*(da12b4)+
(bia1b5)*(da1b5)+(bia2b5)*(da2b5)+
(bia3b5)*(da3b5)+(bia4b5)*(da4b5)+
(bia5b5)*(da5b5)+(bia6b5)*(da6b5)+
(bia7b5)*(da7b5)+(bia8b5)*(da8b5)+
(bia9b5)*(da9b5)+(bia10b5)*(da10b5)+
(bia11b5)*(da11b5)+(bia12b5)*(da12b5)+
bib1c*db1c+bib2c*db2c+bib3c*db3c+bib4c*db4c+bib5c*db5c);
!normalised;
drn=(77.7581-dr)/(77.7581-37.828);

!Job Opportunities;
jom3=0.002;
jom4=0.022;
jok1=2.210;
jok4=0.001;
jok7=0.005;
jok8=0.004;
```

```
jok9=0.576;
joj12=0.004;
joj13=0.004;
joj5=0.01;
joj6=0.01;
joj7=0.01;
joj8=0.01;
jop= jom3*(b1m3+b2m3+b3m3+b4m3+b5m3)+
jom4*(b1m4+b2m4+b3m4+b4m4+b5m4)+
jok4*(b1k4+b2k4+b3k4+b4k4+b5k4)+
jok8*(b1k8+b2k8+b3k8+b4k8+b5k8)+
jok7*(b1k7+b2k7+b3k7+b4k7+b5k7)+
jok1*(b1k1l1+b2k1l1+b3k1l1+b4k1l1+b5k1l1)*0.58/8000+
jok9*(b1k9l1+b2k9l1+b3k9l1+b4k9l1+b5k9l1)*1.05/8000+
joj12*(b1i7j12+b2i7j12+b3i7j12+b4i7j12+b5i7j12)*0.26+
joj13*(b1i7j13+b2i7j13+b3i7j13+b4i7j13+b5i7j13)*0.36+
joj5*(b1i1j5*252.62+b2i1j5*252.62+b3i1j5*252.62+b4i1j5*252.62+b5i1j5*252.62)*
pe+
joj6*(b1i1j6*255.8+b2i1j6*255.8+b3i1j6*255.8+b4i1j6*255.8+b5i1j6*255.8)*pe+
joj7*(b1i1j7*255.27+b2i1j7*255.27+b3i1j7*255.27+b4i1j7*255.27+b5i1j7*255.27)*
pe+
joj8*(b1i1j8*230.23+b2i1j8*230.23+b3i1j8*230.23+b4i1j8*230.23+b5i1j8*230.23)*
pe;
jot=((b1c+b2c+b3c+b4c+b5c)*0.45)/(15*1200);
jo=jot+jop;
!normalised;
jon=(jo-4915.579)/(5340.394-4915.579);

!Single Objective function;
max=0.3856*gpn+0.1283*cfn+0.0779*wfn+0.0511*lfn+0.1576*isin+0.1092*drn+0.0903
*jon;

END
```

E.2 Result of MOO

```
Global optimal solution found.
Objective value:                              0.8594566
Objective bound:                              0.8594566
Infeasibilities:                              0.5960464E-07
Extended solver steps:                                2
Total solver iterations:                           6277
Elapsed runtime seconds:                           1.16

Model Class:                                       MILP

Total variables:                  495
Nonlinear variables:                0
Integer variables:                 83

Total constraints:                376
Nonlinear constraints:              0

Total nonzeros:                  2009
Nonlinear nonzeros:                 0
```

Variable	Value	Reduced Cost
A1S	1550.000	0.000000
A2S	10.00000	0.000000
A3S	3550.000	0.000000
A4S	50.00000	0.000000
A5S	460.0000	0.000000
A6S	270.0000	0.000000
A7S	240.0000	0.000000
A8S	100.0000	0.000000
A9S	0.000000	0.000000
A10S	0.000000	0.000000
A11S	0.000000	0.000000
A12S	0.000000	0.000000
A1PI	560.0000	0.000000
A2PI	0.000000	0.000000
A3PI	670.0000	0.000000
A4PI	320.0000	0.000000
A5PI	0.000000	0.000000
A6PI	1540.000	0.000000
A7PI	0.000000	0.000000
A8PI	170.0000	0.000000
A9PI	200.0000	0.000000
A10PI	0.000000	0.000000
A11PI	0.000000	0.000000
A12PI	0.000000	0.000000
A1PO	0.000000	0.000000
A2PO	0.000000	0.000000
A3PO	0.000000	0.000000
A4PO	1174300.	0.000000
A5PO	0.000000	0.000000

A6PO	0.000000	0.000000
A7PO	939400.0	0.000000
A8PO	352200.0	0.000000
A9PO	0.000000	0.000000
A10PO	1051400.	0.000000
A11PO	469700.0	0.000000
A12PO	704500.0	0.000000
A1P	2770.000	0.000000
A2P	2610.000	0.000000
A3P	1600.000	0.000000
A4P	380.0000	0.000000
A5P	0.000000	0.000000
A6P	0.000000	0.000000
A7P	0.000000	0.000000
A8P	0.000000	0.000000
A9P	0.000000	0.000000
A10P	350.0000	0.000000
A11P	0.000000	0.000000
A12P	0.000000	0.000000
A1	4880.000	0.000000
A2	2620.000	0.000000
A3	5820.000	0.000000
A4	1175050.	0.000000
A5	460.0000	0.000000
A6	1810.000	0.000000
A7	939640.0	0.000000
A8	352470.0	0.000000
A9	200.0000	0.000000
A10	1051750.	0.000000
A11	469700.0	0.000000
A12	704500.0	0.000000
A1B1	0.000000	0.1305841E-06
A1B2	4880.000	0.000000
A1B3	0.000000	0.5861617E-07
A1B4	0.000000	0.1150848E-06
A1B5	0.000000	0.2612867E-06
A2B1	0.000000	0.000000
A2B2	2620.000	0.000000
A2B3	0.000000	0.000000
A2B4	0.000000	0.000000
A2B5	0.000000	0.000000
A3B1	0.000000	0.1422564E-06
A3B2	5820.000	0.000000
A3B3	0.000000	0.5863888E-07
A3B4	0.000000	0.1150753E-06
A3B5	0.000000	0.2539225E-06
A4B1	0.000000	0.4508809E-08
A4B2	1175050.	0.000000
A4B3	0.000000	0.6004690E-07
A4B4	0.000000	0.9355708E-07
A4B5	0.000000	0.1184650E-06
A5B1	0.000000	0.1714731E-06
A5B2	0.000000	0.1160030E-06
A5B3	0.000000	0.1051575E-06
A5B4	460.0000	0.000000
A5B5	0.000000	0.4702758E-07
A6B1	0.000000	0.000000

A6B2	1810.000	0.000000
A6B3	0.000000	0.000000
A6B4	0.000000	0.9383665E-07
A6B5	0.000000	0.1333088E-06
A7B1	0.000000	0.1657929E-06
A7B2	0.000000	0.1467379E-06
A7B3	0.000000	0.1467361E-06
A7B4	939640.0	0.000000
A7B5	0.000000	0.2488831E-07
A8B1	0.000000	0.000000
A8B2	0.000000	0.1757376E-06
A8B3	0.000000	0.1756940E-06
A8B4	352470.0	0.000000
A8B5	0.000000	0.1245980E-07
A9B1	0.000000	0.1808942E-07
A9B2	0.000000	0.1026974E-06
A9B3	0.000000	0.000000
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BIA8B2	0.000000	0.1541048E-01
BIA9B2	0.000000	0.1005031E-01
BIA10B2	1.000000	0.4422138E-02
BIA11B2	1.000000	0.4288134E-02
BIA12B2	0.000000	0.9648300E-02
BIA1B3	0.000000	0.1500847E-01
BIA2B3	0.000000	-0.8547144
BIA3B3	0.000000	0.1420444E-01
BIA4B3	0.000000	0.4556142E-02
BIA5B3	0.000000	0.8710271E-02
BIA6B3	0.000000	0.1474046E-01
BIA7B3	0.000000	0.5896184E-02
BIA8B3	0.000000	0.1286440E-01
BIA9B3	0.000000	0.6432200E-02
BIA10B3	0.000000	0.6968217E-02
BIA11B3	0.000000	0.1742054E-02
BIA12B3	0.000000	0.7102221E-02
BIA1B4	0.000000	0.2036863E-01
BIA2B4	0.000000	-0.8667715
BIA3B4	0.000000	0.1956461E-01
BIA4B4	0.000000	0.1098834E-01
BIA5B4	1.000000	0.4020125E-02
BIA6B4	0.000000	0.1996662E-01
BIA7B4	1.000000	0.6700209E-03
BIA8B4	1.000000	0.5762179E-02
BIA9B4	1.000000	0.5092159E-02
BIA10B4	0.000000	0.1259639E-01
BIA11B4	0.000000	0.7370229E-02
BIA12B4	1.000000	0.1340042E-02
BIA1B5	0.000000	0.2572880E-01
BIA2B5	0.000000	0.1795656E-01
BIA3B5	0.000000	0.2492478E-01
BIA4B5	0.000000	0.1621450E-01
BIA5B5	0.000000	0.2948092E-02
BIA6B5	0.000000	0.2532679E-01
BIA7B5	0.000000	0.5896184E-02
BIA8B5	0.000000	0.1018432E-01
BIA9B5	0.000000	0.9112284E-02
BIA10B5	0.000000	0.1795656E-01

BIA11B5	0.000000	0.1273040E-01
BIA12B5	0.000000	0.4958154E-02
BIB1C	0.000000	0.1855958E-01
BIB2C	1.000000	0.1412404E-01
BIB3C	0.000000	0.1159136E-01
BIB4C	1.000000	0.8790674E-02
BIB5C	0.000000	0.1340042E-02
DR	37.93900	0.000000
DRN	1.000000	0.000000
JOM3	0.2000000E-02	0.000000
JOM4	0.2200000E-01	0.000000
JOK1	2.210000	0.000000
JOK4	0.1000000E-02	0.000000
JOK7	0.5000000E-02	0.000000
JOK8	0.4000000E-02	0.000000
JOK9	0.5760000	0.000000
JOJ12	0.4000000E-02	0.000000
JOJ13	0.4000000E-02	0.000000
JOJ5	0.1000000E-01	0.000000
JOJ6	0.1000000E-01	0.000000
JOJ7	0.1000000E-01	0.000000
JOJ8	0.1000000E-01	0.000000
JOP	5332.172	0.000000
JOT	38.11710	0.000000
JO	5370.289	0.000000
JON	1.070372	0.000000