BIOMASS SUPPLY CHAIN OPTIMISATION: CONSIDERATION OF UNDERUTILISED BIOMASS VIA ELEMENT TARGETING APPROACH

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ABSTRACT

Achieving a sustainable process system is one of the main focuses in research and development throughout the world. Development in renewable resources is at the peak to replace and reduce the usage of fossil fuel in chemical and energy production. Bio-resources have shown great potential to accomplish a sustainable system, especially bio-waste which also known as biomass, to avoid interruption of food supplement within the supply chain network. However, worldwide implementation of biomass-based process technology is yet to be feasible due to high logistic cost, complexity of biomass properties, fluctuation of biomass availability, and relatively low conversion rate in biomass conversion technologies. Unique regional biomass system further creates research gaps as researches are conducted independently to only focus on specific biomass species available within the region. This raises issue of underutilisation of biomass where biomasses value are not used in the full potential, or ignorance of certain species of biomass (such as food waste, fruit shells and energy crop) in research development.

This thesis specifically evaluated the current issues in biomass supply chain network management to enhance the feasibility of biomass industry implementation. The main objective of this thesis is to improve the biomass supply chain network management by integrating underutilised biomasses into existing biomass process plant (built) without major modification on the current process technologies such as equipment redesign or modifications. Underutilised biomasses are referring to those species that yet to have well-developed application (pilot plant scale) or potential biomasses that were ignored in a regional area due to issues such as low availability. This thesis discusses in detail on the relevant previous research works and supporting materials toward the introduction of novel philosophy, element targeting approach, which suggested selection of biomass feedstock via element characteristics instead of biomass species to consider underutilised biomasses into the system. Upon verification of the approach based on literature data and experimental work, element targeting approach is integrated into biomass supply chain optimisation model. The proposed mathematical models enable consideration of underutilised biomasses, and demonstration case studies results have shown promising improvement over the conventional approaches and its capability to handle fluctuation issues in biomass availability.

LIST OF PUBLICATION

This research work contributed a number of novel breakthroughs. Below summaries all publications produced in conjunction with the thesis.

Journal paper:

I. Lim, C.H., Lam, H.L. 2014. Biomass Demand-Resources Value Targeting. Energy Conversion and Management, 87, 1202-1209.

II. Lim, C.H., Lam, H.L. 2016. Biomass supply chain optimisation via novel Biomass Element Life Cycle Analysis (BELCA). Applied Energy, 161, 733-745.

III. Lim, C.H., Mohammed, I.Y., Abakr, Y.A., Kazi, F.K., Yusup, S., Lam, H.L. 2016. Novel Input-Output Prediction Approach for Biomass Pyrolysis. Journal of Cleaner Production, 136(B), 51-61. DOI:10.1016/j.jclepro.2016.04.141

IV. Mohammed, I.Y.., Lim, C.H., Kazi, F.K., Yusup, S., Lam, H.L., Abakr, Y.A. 2016. Co-pyrolysis of rice husk with underutilized biomass species: a sustainable route for production of precursors for fuels and valuable chemicals. Waste Biomass Valorization. DOI 10.1007/s12649-016-9599-9

Conference:

I. Lam, H., Ng, W.P.Q., Lim, E.C.H., Tang, J.P. 2014. Novel Computer-Aided Approach for Biomass Operational Management, 34, 783-788. (8th International Conference on Foundations of Computer-Aided Process Design, 13-17 July 2014, Washington, USA.)

II. Lim, C.H., Lam, H.L. 2013. Biomass Demand-Resources Value Targeting. Chemical Engineering Transactions, 35, 631-637. (16th Conference Process Integration Modelling and Optimisation for Energy Saving and Pollution Reduction, 29-2 October 2013, Rhodes, Greece.)

III. Lim, C.H., Lam, H.L. 2013. Novel Biomass Classification with Element-Value Method. 8th Conference on Sustainable Development of Energy, Water and Environment Systems, 22-27 September 2013, Dubrovnik, Croatia. (full paper accepted and awarded as best poster)

IV. Lim, C.H., Lam, H.L. 2014. Introduction of Novel Analysis Technique: Biomass element Life Cycle Analysis (BELCA). Chemical Engineering Transactions, 39, 337-342. (17th Conference Process Integration Modelling and Optimisation for Energy Saving and Pollution Reduction, 23-27 August 2014, Prague, Czech Republic.)

V. Lim, C.H., Mohammed, I.Y., Abakr, Y.A., Kazi, F.K., Yusup, S., Lam, H.L. 2015. Element Characteristic Tolerance for Semi-batch Biomass Pyrolysis, Chemical Engineering Transactions, 45, 1285-1290. (18th Conference Process Integration Modelling and Optimisation for Energy Saving and Pollution Reduction, 23-27 August 2015, Kuching, Malaysia.)

VI. Lim, C.H., Lam, H.L. 2015. Functionality of Element Targeting Approach in Dynamic Biomass Resources Supply Chain System, Chemical Engineering Transactions, 45, 1855-1860. (18th Conference Process Integration Modelling and Optimisation for Energy Saving and Pollution Reduction, 23-27 August 2015, Kuching, Malaysia.)

VII. Lim, C.H., Lam, H.L. 2016. Element Targeting Approach for Mutiple Biomass Feedstock Conversion, Proceedings of 2nd South East European Conference on Sustainable Development of Energy, Water and Environment Systems, SDEWES.SEE 2016.0266, 1-18. (2nd South East European Conference on Sustainable Development of Energy, Water and Environment Systems, Piran, Slovania.)

VIII. Lim, C.H., Lam, H.L. 2016. Overview of biomass supply chain optimisation model: HAZOP approach, Conference Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, 28-31 August, 2016, Prague, Czech Republic. (Full paper accepted and invited for special issue.)

Out of the list of paper publication stated above, some of the papers are in parallel with the core of the chapter within this thesis. Upon research gaps identification in Chapter 2, the element targeting approach introduced in Chapter 3 is the main core of the list of publication above. All of the published papers above discussed around the approach in different point of view, in order to solidify the philosophy. The overall concept of element targeting and its potential application is firstly published in conference paper No. II. Upon further research and development, the work to verify the proposed concept via laboratory experiment, which will be discussed in detail in Chapter 5, generated a conference paper (No.V) and invited as special issue and published as journal paper No. III in the list above. As the main objective of this research work, Chapter 6 discusses the applications of element targeting approach in biomass supply chain optimisation network. This work generates the most publication including journal papers No. I and II, as well as conference papers No. III, IV, and VI, which discuss on the Demand-Resources Value Targeting approach and Biomass Element Life Cycle Analysis approach.

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List of Nomenclature

Abbreviations	
Ash	Ash content
BECA	Biomass Element Cycle Analysis
BELCA	Biomass Element Life Cycle Analysis
C	Carbon content
Cell	Cellulose content
DRVT	Demand-Resources Value Targeting
EFB	Empty fruit bunch
Ext	Extractive
FC	Fixed carbon content
f_e	Element deviation factor
GAMS	General Algebraic Modelling System
GIS	Geographical Information System
H	Hydrogen content
H/C	Hydrogen over carbon ratio
HAZOP	Hazard and operability study
Hcel	Hemicellulose content
HHV	Higher heating value
HV	Heat value
HW	Hard wood
LCA	Life cycle assessment
LHV	Lower heating value
Lig	Lignin content
M	Molar mass
MC	Moisture content
MILP	Mixed integer linear programming
N	Nitrogen content
NGS	Napier grass stem
O	Oxygen content
O/C	Oxygen over carbon ratio
OPF	Oil palm fronds
PKT	Palm kernel trunk
PMF	Palm Mesocarp Fibre
PS	Palm shell

Abbreviations	
RH	Rice husk
RVP	Reid Vapour Pressure
S	Sulphur content
Sago	Sago biomass
SSF	Simultaneous Saccharification and Fermentation
SW	Soft wood
VM	Volatile matter content
ρ	Liquid density
x	Mole fraction
$\Delta * G^E$	Gibbs free energy
A_1 and A_2:	Empirical parameters estimated via minimum square techniques
$\dot{T}$	Temperature function
ν	Kinematic viscosity
λ	Thermal conductivity
µ	Dynamic viscosity
Set/Indexes	
i	Resources
j, jp	Technology (Process plant) inlet, outlet
k	Demand
m	Material (biomass and product)
e	Element properties
r	Mode of transportation
Variables	
RtoT (i, m, j)	Mass of each material transported from Resources ***i*** to Technology ***j***
TtoT (jp, m, j)	Mass of each material (biomass only) transported from Technology ***jp*** to Technology ***j***
TtoD (jp, m, k)	Mass of each material transported from Technology ***j*** to Demand ***k***

Parameters	
Resource *(i, m)*	Material m availability at each Resources ***i***
Element*(m, e)*	Element properties e for each Material ***m***
E_upper*(e, j)*	Upper bound of Element Properties ***e*** at each Technology ***j***
E_lower*(e, j)*	Lower bound of Element Properties ***e*** at each Technology ***j***
E_ori*(e, j)*	Original biomass Element Properties ***e*** at each Technology ***j***
Upper_Demand*(m, k)*	Lower demand of Material ***m*** at each local Demand ***k***
Lower_Demand*(m,k)*	Upper demand of Material ***m*** at each local Demand ***k***
TMatRecT$("j = j")$	Total Material ***m*** received at a particular Technolgy ***j***
ele_yield$("j{=}j", m, jp)$	Process conversion factor of a particular technology ***j*** to generate product ***m*** at same technology output ***jp*** based on element conversion
mass_yield$("j{=}j", m, jp)$	Process conversion factor of a particular technology ***j*** to generate product ***m*** at same technology output ***jp*** based on mass conversion
Distance_RtoT*(i, j,r)*	Distance from Resources ***i*** to Technology ***j***
Distance_TtoT*(j, jp,r)*	Distance from Technology ***j*** to Technology ***jp***
Distance_TtoD*(jp, k,r)*	Distance from Technology ***jp*** to Demand ***k***
Transcost*(r)*	Transportation cost of material per t per km
TTranscost	Total transportation cost
TtoTfactor(m, j)	Recycle material, ***m*** acceptance factor at each technology, ***j***
Value *(m)*	Selling value of respective Material ***m***
Equations	
MatRecT*(m, j)*	Material ***m*** received at each Technology ***j***
TMatRecT*(j)*	Total Material ***m*** received at each Technology ***j***
MatGenT*(m,jp)*	Material ***m*** generated at each Technology ***jp***
EleRecT*(m, e, j)*	Element Properties of each Material (***m***, ***e***) received at each Technology ***j***
Cost_TtoJ*(i, j)*	Transportation cost from Resources ***i*** to Technology ***j***
Cost_JtoJP*(j, jp)*	Transportation cost from Technology ***j*** to Technology ***jp***
Cost_JPtoK*(jp, k)*	Transportation cost from Technology ***jp*** to Demand ***k***
MatProCost*(m,jp)*	Production cost of each material ***m*** at each Technology ***jp***
TotProCost	Total production cost for all product generated
profit	Profit without consideration of transportation cost
totalprofit	Total profit with consideration of transportation cost

Chapter 1: INTRODUCTION

Environmental impacts from chemical processes have progressively become the main concern in the world due to over-dependant and over-used of fossil fuel. Global warming and environmental pollution constantly remind public on the issue of overused of natural resources. Thus, the terminology of sustainability became more familiar in each area of development and became one of the main focuses in research. However, at current state, many processes have yet to achieve sustainability, especially in fossil fuel or petroleum industry as they are the dominant resource for energy and downstream chemical products. In order to achieve sustainable system, utilisation of renewable resources has to be improved. Utilisation of bio-resources from plantation is initially the main focus of sustainable system development. However, ethical issues were araised in the First Generation Bio-recourses with the argument and objection of utilising food crops as the feedstock for chemical processes. Therefore, current research development are moving towards Second and Third Bio-resources which utilises lignocellulosic biomass and algae. On the other hand, due to complex nature and characteristic of bio-resources, biomass and algae have yet to be fully implemented in industry scale. Some of the main challenges are high transportation cost and complex supply chain management which leads to underutilisation of biomass. This research contributes novel approaches in biomass supply chain optimisation by consideration of underutilised biomass.

1.1 Background

With the awareness of global sustainability, biomass is one of the highly anticipated alternative resources for many processes. Biomass is biodegradable waste or side product generated from bio-industry. High availability, enhance development of rural area, zero carbon dioxide balance and multiple adaptation in varies technologies gave biomass more advantages with respect to other renewable resources (Á.Murillo et al., 2015). In addition, converting biomass into useful downstream products is considered to be a more environmental friendly, cost effective and at the same time reduces waste management efforts. Nevertheless, full implementation of biomass in large industrial scale is yet to be proven feasible as biomass is generally treated as negative value by-product and the main challenge in biomass implementation is the high logistic cost. For example, 90% of biomass ethanol production cost of supplying biomass is logistic cost (Eksioğlu *et al.*, 2009). This proves the importance of supply chain network management and optimisation in biomass industry.

Numerous integration techniques were introduced in biomass supply chain optimisation to rectify the transportation network and biomass storage setbacks. However, most of the supply chain integrations do not consider the quality of biomass utilisation. Therefore, the true value of biomasses are not been fully utilised due to the lack of analysis on the bigger picture of biomass utilisation within the whole system and their best applications. For example, Empty Fruit Bunch (EFB) is normally used for mulching in many palm oil mills for soil nutrient recovery due to its convenience of utilising the resources locally. However, EFB has the potential value to convert into a higher value product such as fertiliser or bio-fuel prior to processes. Lack of systematic determination of biomass utilisation restrains the chances of alternative applications of biomass. Another factor of underutilisation of biomass is the over-focus on main stream biomass which leads to underdevelopment of many other potential biomasses. For example, forestry residues, wet waste from daily activities, tree branches, energy crops and many non-mainstream biomasses are widely available and have the potential to be used as biofuel or downstream products. However, in current state, not many researches and biomass supply chain integration have considered these non-mainstream biomasses. These yet to be commercialist biomasses are *classified as underutilised biomass*. This terminology can be used as a general biomass classification to define any specific biomass species where their applications are yet to be explored. Biomass industry and supply chain system is usually a regional problem, where depending on the biomass distribution and available species, each regional system has their own challenges and optimum solutions. Hence, there are two approaches to define the underutilised biomass, i) in general, any biomass species that yet to have well established technology (pilot plants size research) based on literature; ii) in biomass regional system, any biomass species that does not integrated into the existing biomass supply chain management. The later approach depends on the regional cases, and different region can have different classification of underutilised biomass. For example, palm based biomass are well developed in tropical country such as Malaysia. Thus it is not classified as underutilised biomass in this region. However, in other region such as United State, it is not the main consideration in the supply chain due to limited availability of palm. Nevertheless, the potential of the biomass should not be ignored. Thus in this case, palm based biomass will be classified as underutilised biomass in that particular region, with the potential as a supportive alternative resources for the regional supply chain network.

In this thesis, a novel approach of element targeting is introduced to improve the specific issues stated above. This systematic approach is introduced to analysis biomass potential and their application. With such approach, underutilised biomasses can be integrated into existing biomass supply chain network management within each regional system, and further improve the overall system.

1.2 Problem statement

Research and development has proven that biomasses are one of the best alternative resources for process industry to achieve sustainability. However, implementation of biomass in industrial scale is yet to be feasible in many regional systems. Two main challenges to be undertake in this research are, (i) high logistic cost and the complexity of biomass supply chain; (ii) biomass underutilisation (not using the best value from the biomass application). This thesis resolves both problems by evaluating the possibility and feasibility in improving and optimising regional biomass supply chain network via consideration of underutilised biomass into the system. In order to integrate underutilised biomass into the existing system, a systematic biomass classification approach is required to incorporate underutilised biomass into current supply chain.

1.3 Objective of research

The objective of this research is to improve the existing biomass industry by optimising biomass supply chain network via consideration of underutilised biomass within the system. It can be categorised into several phases, which include: i) To identify research gaps and potential development on existing biomass supply chain optimisation approaches; ii) To develop an approach to evaluate potential application of underutilised biomass; iii) To develop biomass supply chain optimisation model with integration of underutilised biomass.

1.4 Scope of research

Scopes of research focuses on three areas; i) biomass supply chain; ii) existing biomass process technologies; and iii) underutilised biomass. The proposed research areas are supported with literature, laboratory work and mathematical optimisation modelling software, General Algebraic Modelling System (GAMS). Figure 1-1 illustrates the overall scope of work for this research. Detailed explanation for each scope is further discussed below:

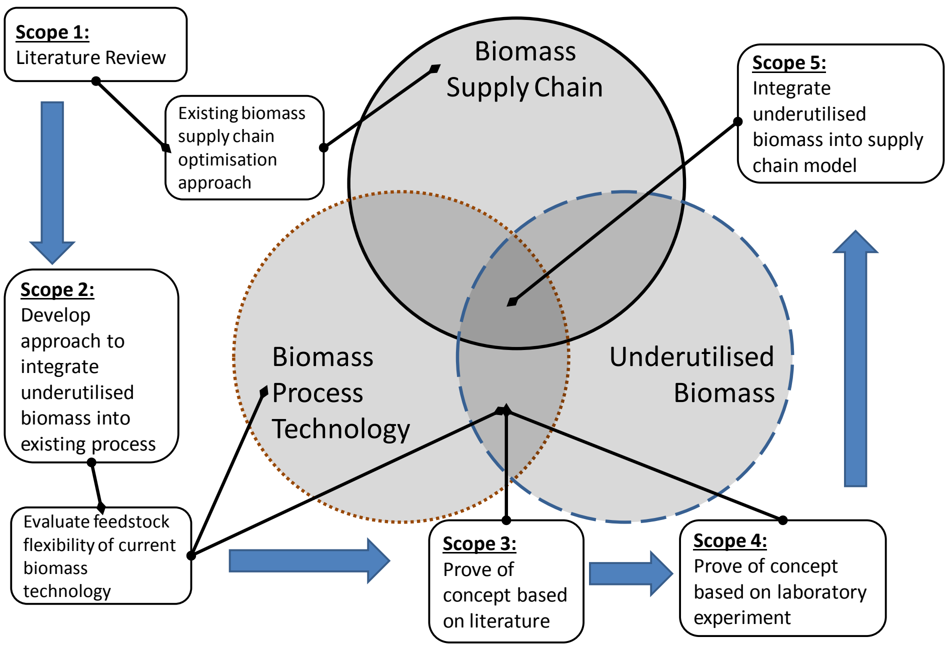


Figure 1- 1: Overall scope of work with integration between biomass supply chain, underutilised and biomass process industry

I. *Literature review on existing biomass supply chain optimisation approaches*

Detailed literature review on various optimisation approaches is essential in order to understand previous approach proposed by researchers. This is to ensure novelty of this work and provides an overall understanding of current research and development state in this field of research. Analysis on existing optimisation model which involved consideration of underutilised biomass is conducted to further identify potential development from the existing approaches.

II. *Develop systematic approach to integrate underutilised biomass into existing biomass system*

In this scope, a systematic approach is introduced to integrate underutilised biomass into existing biomass process technology. The proposed approach is expected to be applicable into existing biomass process. Underutilised biomasses are targeted to be integrated into the system without major process modification such as equipment redesign. This minimises design modification cost and encourages acceptance of underutilised biomass within the system. Thus, analysis on the current biomass process technology is essential to ensure the methodology or approach is feasible in enhancing feedstock flexibility of respective process by incorporating underutilised biomasses into the system.

III. *Concept verification of applicability of proposed approach based on literature*

Verification of the proposed approach is very important to analyse the feasibility of implementation in real life before initiating the development of optimisation model. In this scope, the main objective is to apply proposed approach solely based on existing literature. This is the first stage analysis on the applicability of the proposed approach based on developed biomass process technologies. Upon the verification, the approach can be applied into existing researches as an extension work to enhance biomass feedstock flexibility. This will gives credit to the current technology development and minimises the requirement of developing new technology from scratch.

IV. *Concept verification of applicability of proposed approach based on laboratory experiment*

The next scope of work moves toward laboratory experiment to verify the concept. Similarly, this scope is to analyse the integrity of proposed approach in laboratory performance. Experimental work in laboratory enables more control on variables and focuses on the study of feedstock flexibility of respective biomass technology. This will further solidify the concept and feasibility of the proposed approach.

V. *Construct biomass supply chain optimisation model with integration of underutilised biomass*

Ultimately, the final scope of the thesis focuses on the construction of biomass supply chain optimisation models to include underutilised biomass into the existing system. Mathematical supply chain models are developed to consider underutilised biomasses based on the proposed approach in Scope 2. The model is expected to improve regional biomass supply chain management with consideration of underutilised biomass as alternative resources. The results are compared to the current biomass supply chain network that does not consider underutilised biomass as potential resources. Functionality of the proposed model is tested to improve other issues, such as uncertainty in resources availability, fluctuation in biomass price and transportation cost.

1.5 Research strategy

In order to ensure all research scopes are achieved, a research strategy is properly planned and produced as the guideline throughout the research period. Figure 1-2 shows the stage-by-stage research strategy and procedures that leads to the ultimate research outcomes. The strategy plan consists of three main parts, i) detailed literature review to identify research gaps and to propose novel philosophy, ii) prove of concept for proposed methodology, and iii) integration of proposed approach into biomass supply chain optimisation model.

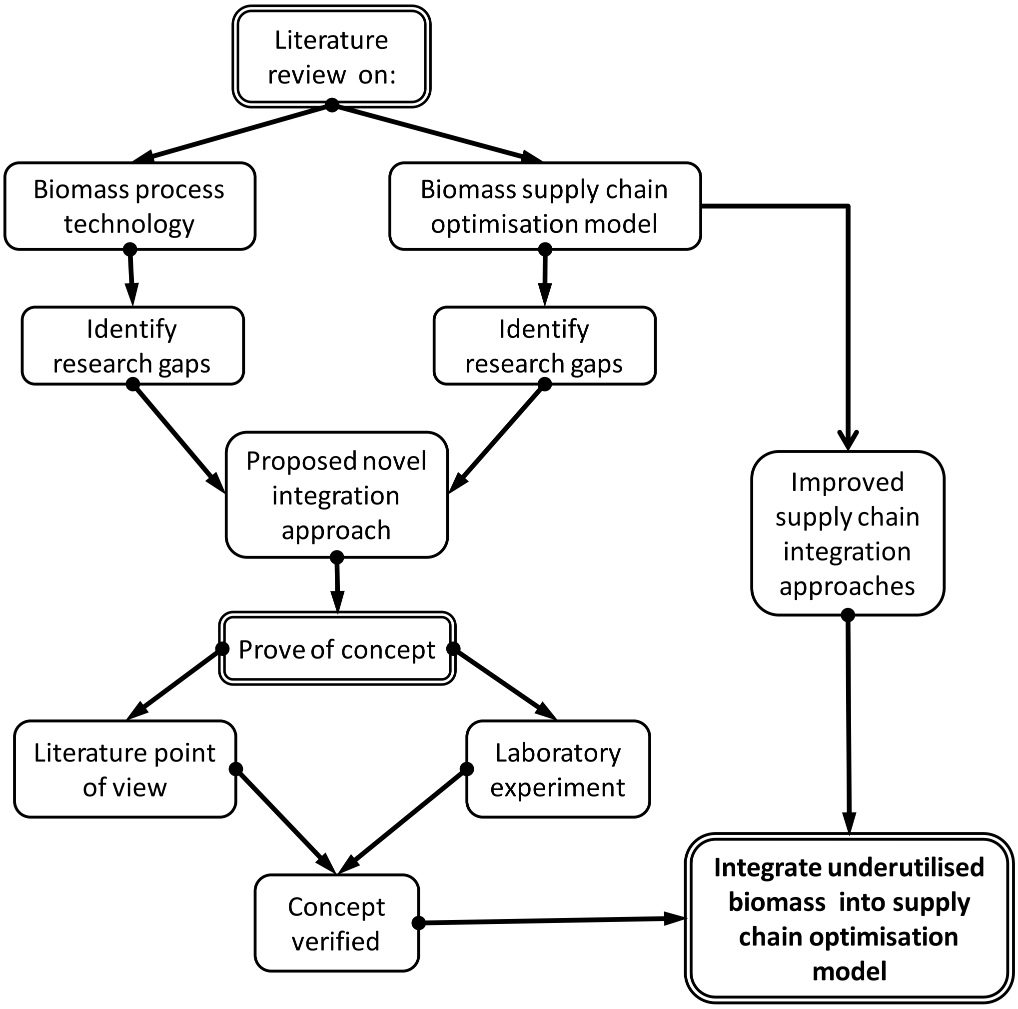


Figure 1- 2: Overall research strategy and procedures

1.6 Original contribution of research

This research offers novel contributions in biomass supply chain optimisation and the discovery of potential application of underutilised biomass. The research has contributed to several conferences and journal publications as listed in the List of Publications. The main contributions yielded from this research are stated below:

I. *Inclusion of underutilised biomass in biomass process*

A novel and systematic approach to evaluate the feasibility of implementing underutilised biomass species into existing biomass technology via element targeting approach. This approach is the core concept in all the papers generated from the work stated in the List of Publications.

II. *Improve flexibility of feedstock selection on current biomass process technologies*

Introduce systematic approach that enables higher tolerance of feedstock selection in biomass process without major design modification. This contribution is acknowledged by the acceptance of journal paper: *Lim, C.H., Mohammed, I.Y., Abakr, Y.A., Kazi, F.K., Yusup, S., Lam, H.L. 2016. Novel Input-Output Prediction Approach for Biomass Pyrolysis, Journal of Cleaner Production. (in press).*

III. *Improve overall biomass supply chain system*

Improve overall biomass supply chain network performance via inclusion of underutilised biomass. This contribution has been demonstrated in published journal paper: i) Lim, C.H., Lam, H.L. 2014. Biomass Demand-Resources Value Targeting. Energy Conversion and Management, 87, 1202-1209., and ii) Lim, C.H., Lam, H.L. 2015. Biomass supply chain optimisation via novel Biomass Element Life Cycle Analysis (BELCA). Applied Energy, 161, 733-745.

IV. *Management and decision making tool*

Provide a systematic evaluation platform to access feasibility of underutilised biomass implementation based on the supply chain optimisation model. Similarly, this contribution has been demonstrated in the biomass supply chain models published in: i) Lim, C.H., Lam, H.L. 2014a. Biomass Demand-Resources Value Targeting. Energy Conversion and Management, 87, 1202-1209., and ii) Lim, C.H., Lam, H.L. 2015. Biomass supply chain optimisation via novel Biomass Element Life Cycle Analysis (BELCA). Applied Energy, 161, 733-745.

1.7 Thesis outline

The following describes the outline of this thesis and the expected outcomes. The thesis is separated into five main chapters, beginning from Chapter 2 to Chapter 6, and followed by a concluding chapter. The research is kick started with detail literature review of existing biomass supply chain optimisation approaches, which were discussed in the next chapter, Chapter 2. A systematic Hazard and Operability study approach is integrated into the literature review to identify research gaps at each stage of biomass supply chain network. Recommendations are suggested as the mitigation for each current research limitation, which were mainly due to underutilisation of biomass.

Upon literature review, a novel integration approach, namely element targeting, is proposed in Chapter 3 to integrate underutilised biomass into the existing biomass process technologies. The approach uses biomass element characteristics as the feedstock selection criteria instead of biomass species that was used in the conventional approaches. Detail methodology is discussed within the same chapter. Due to the novelty nature of the philosophy, the concept is verified in Chapters 4 and 5 to ensure its applicability in real life scenario. Chapter 4 focuses on the verification of concept based on literature data. This scope is to testify the implementation of the approach in existing biomass process technology, such that no major modification onto existing equipments and process are required when implementing element targeting approach. Due to the difference in research interest, information solely based on literature is unable to provide a complete verification process. Thus, a specific laboratory procedure is constructed in Chapter 5 to further verify the concept of element targeting approach. Biomass pyrolysis experiment is selected as the verification platform.

Upon verification of the element targeting concept, this approach is integrated into biomass supply chain optimisation model. Construction of the mathematical models is discussed in Chapter 6 with supporting demonstration case studies to highlight the improvement as compared to the existing approaches. The main objective is to allow the model to consider underutilised biomass as alternative biomass resources in order to minimise overall logistic and production cost. This research is concluded in Chapter 7 and followed by recommendation of future works for sustainable improvement and research practice.

Chapter 2:
CRITICAL REVIEW: THE DEVELOPMENT OF BIOMASS SUPPLY CHAIN AND ITS RESEARCH GAPS

As discussed in previous chapter, biomass plays a big role in current research and development as an alternative green resource to achieve sustainability. However, implementation of biomass industry is still a major challenge, mainly due to various supply chain management limitations. Generally, the main challenges faced in biomass supply chain management are fluctuation of biomass availability, unique properties of each biomass species, harvesting, transportation and logistics issues, facility location, and development of biomass conversion technologies. Seasonality of biomass and weather uncertainty also causes difficulty in biomass supply chain management. Researchers have been working on these matters by introducing various biomass supply chain optimisation models to determine the optimum biomass system. The approaches includes deterministic, stochastic, hybrid, and IT-driven models (Sharma et al., 2013). Although many efforts have contributed into improvement of biomass supply chain, there are new challenges and issues to overcome. In this chapter, an analysis is conducted to evaluate the current state of biomass supply chain modelling and investigate in detail the potential research gaps to improve the feasibility of biomass implementation. A systematic approach is implemented in the study to ensure high quality review. For the first time, *Hazard and Operability Study (HAZOP)* is implemented to review the existing biomass supply chain. This approach is generally used in chemical process plant to ensure process safety and operation. The traditional HAZOP methodology is modified into a more robust platform for general literature review approach. Based on the overview of biomass supply chain system via HAZOP approach, several critical issues in biomass supply chain are identified. These limitations are recommended as research gaps for future work in order to enhance the biomass supply chain management.

2.1 Methodology

HAZOP approach is a brain-storming session among expertise to identify potential process hazard, forecasting potential consequence, analysis of adequacy of existing safeguard/solution, and finally provide recommendation if necessary. According to Herrera et al. (2015), HAZOP methodology was originally created for chemical industries as a safety tool; nonetheless, its application has extended to other field such as risk assessment in medical procedures and risk analysis in supply chain management. The advantage of HAZOP methodology is the systematic evaluation process: where it divides the system into several sections and analyse each section based on guide words. This process provides a complete review with consistency and standardisation, hence will result in better quality of review outcomes.

As the original application of HAZOP methodology is designed for process and operability hazard identification, the general procedures are modified to be applied into literature review. The modified methodology consists of hazard identification, consequence, safeguard/current solutions, and recommendation; which are similar to the original HAZOP methodology. Table 2-1 shows the proposed HAZOP methodology for literature review, which will be implemented in biomass supply chain optimisation.

Table 2- 1: HAZOP methodology for literature review

Procedures	Descriptions
Step 1: Identify scope of work	In traditional process HAZOP, process flow diagram, and piping and instrumentation diagram are common documents used to determine the scope of work. However in this case, the best way to present the scope of work is via block diagrams. Block diagrams are constructed to evaluate the overall system and to show the relations between each section. The more detailed block diagram provided the better quality of assessment. See Figure 2-1 for biomass supply chain system for this study.
Step 2: Define node	Node definition is conducted by splitting the overall system into sections. This step reduces the discussion coverage and provides a clear boundary to enhance the focus in hazard identification in each section. For example, see Figure 2-1 for the node definition of proposed biomass supply chain system for this study.

Table 2-1: HAZOP methodology for literature review (continue)

Procedures	Descriptions
Step 3: Define deviations and guidewords	All potential deviations of process (change of parameter) are pre-defined before the analysis. This is to ensure systematic discussion with minimum astray. Guidewords are a set of pre-defined key words to trigger imagination in hazards identification and help to focus in the assessment. Noted that deviations and guidewords can be different for each system. The pre-defined deviations for this study are quality, quantity, logistic, and market cost/value, while the guidewords are more/higher, less/no and less/lower.
Step 4: Define assumption list	Assumption list is required to clarify the limitation of the study. This limits credibility of each potential hazard and ensures the discussion is within a credible scenario.
Step 5: Identify possible causes of deviation based on guidewords within a selected node	Select a pre-defined node in Step 2, brainstorm all credible cause of hazard within the node based on pre-defined guidewords. Discussion should focus within the current node. All causes of deviation outside the discussing node are to be ignored for time being and to be discussed later.
Step 6: Identify consequences to the system due to deviation	From the identified causes, determine the ultimate (worst case scenario) consequence to the system. Global consequence should be considered to evaluate the impact of respective deviation to the upstream or downstream of the system.
Step 7: Identify existing safeguard/current solution	In this case, existing safeguard is based on the availability of the literature to prevent the cause and consequence. In other words, if there is an approached proposed by researcher to rectify the cause and consequence, the approach is considered as one of the safeguard/mitigation.
Step 8: Propose recommendation if insufficient safeguard/mitigation	In case of no or less researchers have worked on the cause and consequence, or the existing safeguard is not adequate, recommendation(s) should be provided. The recommendation can be listed as potential future work. This will be highlighted as research gaps for improvement.
Step 9: Next guideword	Repeat step 5 to step 8 for next guideword within the same deviation until all guidewords are addressed.
Step 10: Next deviation	Repeat step 5 to step 9 for next deviation within the same node until all deviations are addressed.
Step 11: Next node	Repeat step 5 to step 10 for next node until all nodes are addressed.

2.2 Implementation of HAZOP approach in literature review of biomass supply chain optimisation model

Based on the proposed HAZOP methodology, overview of the current biomass supply chain optimisation model is constructed. The main objective of the study is to identify credible process hazard in biomass supply chain, and determine the availability of adequate development in biomass supply chain optimisation which act as the safeguard for identified process hazards. Recommendations are proposed on issues that are yet to be rectified. This gives an overview of the current state of biomass supply chain optimisation and the discovery of potential research gaps as future works.

2.2.1. Literature review procedure

In industry application, HAZOP brainstorming workshop is normally attended by several expertises to evaluate the proposed scope of work. When translate this methodology into literature review, a consistent brainstorming sessions is applied to constantly update the review based on the latest literature. The brainstorming session is conducted by individuals, with support from collaborators and colleagues to identify as many process hazards as possible. This case study was conducted by the author and his supervisor DDr. Hon Loong Lam. First, scope of work of the study is defined using block diagram as shown in Figure 2-1, which presented in 4 nodes: (i) biomass resources, (ii) conversion processes, (iii) transportation/logistic, and (iv) product demand. Since this HAZOP study is focused on the biomass supply chain problems, the deviations to be considered are listed as: (i) quantity, (ii) quality, (iii) logistic/transportation, and (iv) market value/cost. The guidewords used in this case study are: i) More/Higher and ii) Less/Lower/No, which are applicable for each deviation. Several HAZOP assumptions are considered and listed as following:

- No double jeopardy, only single failure or process hazard is considered at a time. Multiple failures or hazards are considered to have low possibility of occurrence.
- Causes of deviation to be focus on particular node that is being discussed, but consequences of the deviation can be globally discussed within the system.

- Any form of biomass supply chain optimisation model available in literature is considered as safeguard. The safeguards are evaluated based on the general approach and objective of the model. Each proposed approach is considered to be applicable to all similar biomass species and process system.

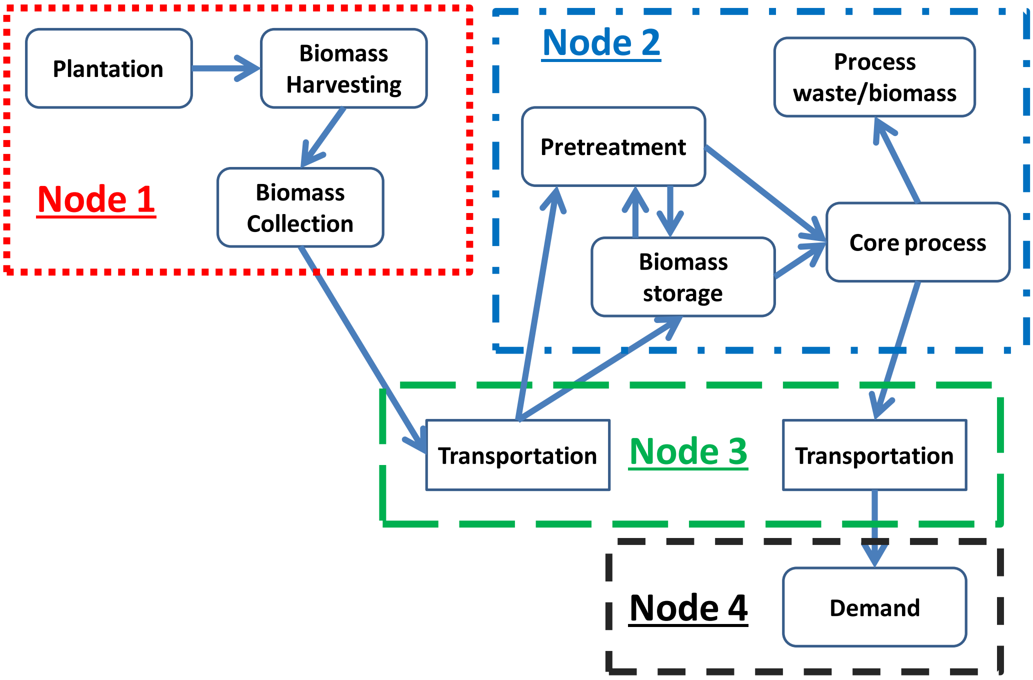


Figure 2- 1: Node identification for generic biomass supply chain system

Table 2-2 summaries the differences of conventional HAZOP methodology used in industry and the proposed HAZOP methodology applied into literature review of biomass supply chain optimisation models.

Table 2- 2: Comparison between industrial HAZOP methodology and the proposed literature review HAZOP methodology

	Industrial HAZOP methodology	**Literature review HAZOP methodology: Biomass supply chain optimisation model**
Personnel involvement	Technology/design expertise	Literature review authors and collaborators
Scope of work	Pre-defined based on project	Determine based on research interest
Documents	Piping and Instrumentation Diagram, Process Flow Diagram, Process Layout, Control Logic	Block diagram developed from scope of work
Deviations	Depending on process nature, typically consist of Flow, Temperature, Pressure, Level, Corrosion/Erosion, Instrumentation, Contamination, Maintenance/Operation, and Others.	Only focus o Quantity, Quality, Logistic/Transportation, and Market Value/Cost, which is relevant to biomass supply chain
Guidewords	No, Less, Reverse, High, and Low	More, Higher, Less, Lower, and No
Safeguards	Based on existing process control system	Based on available literature to tackle the issue
Recommendations	Proposed to improve process safety, such as provide additional safety valve	Proposed as potential research gaps

2.2.2. Literature reviews outcomes

Tables 2-3 to 2-6 summarise the HAZOP discussion. Each of the credible causes of deviation and respective consequences were discussed. Sections 2.2.2.1 to 2.2.2.6 summarised the existing biomass supply chain optimisation modelling approaches available in literature, which acted as safeguards for this HAZOP study. Following describes the process of biomass supply chain optimisation models review via HAZOP approach. The demonstration is based on the first cause of deviation in Table 2-3, which focused on Note 1 in Figure 2-1. Using the first guideword and deviation, More Quantity, the brainstorming session suggested a (the first) cause of deviation, which is due to peak season of plantation. Then, all possible consequences to the whole system were brainstormed, which concluded to be i) More biomass generation resulting in potential underutilisation of biomass, and ii) Potential environmental pollution due to improper biomass waste management. Review on existing literature on biomass supply chain optimisation models was conducted to identify potential rectification to prevent the deviation and consequence. Review outcome has identified that seasonal biomass problems are evaluated by researchers, but less has studied impact of over-supply. For example, Section 2.2.2.1 discussed that this issue was tackled by Shabani et al. (2014) and Eksioğlu et al. (2009), and Kim et al. (2011) evaluated uncertainties in biomass availability. Due to less effort was put into the issue of over-supply, consideration of alternative application for excessive biomass was proposed as a potential research gaps. The procedure is continued to brainstorm other cause of deviation using the same guideword, followed by the next guideword and next Node until all guidewords in all Nodes are covered.

2.2.2.1. Biomass fluctuation:

One of the main challenges in biomass supply chain is the fluctuation of the variables such as biomass availability, biomass quality, biomass cost, product demand, and product price. In order to rectify these problems, "scenario based" optimisation models are constructed to rectify the fluctuations. Stochastic optimisation approach is later introduced to randomise variables within the model to provide an overall optimal solution for all scenarios. Each biomass supply chain model is constructed for respective supply chain sectors. Shabani et al. (2014) constructed a multi-period tactical model to optimise fluctuation of monthly forest biomass availability for a power plant. Seasonal biomass was tackled by Eksioğlu et al. (2009) to optimise biomass supply chain with fluctuation in biomass availability. Uncertainty in logistic is investigated by researchers, such as Kazemzadeh and Hu (2013) evaluated the fluctuation in transportation cost, including uncertainty in fuel cost, and biomass collection and loading cost. Kim et al. (2011) considered uncertainty in biomass availability, conversion yield, maximum product demand, and product price in bio-fuel supply chain system. Similarly, a mixed integer linear programming (MILP) model for bio-ethanol was developed to consider price uncertainty including biomass cost and bio-ethanol selling price (Das-Mas et al., 2011). Uncertainty in total market demand (in terms of quantity) was evaluated with four discrete scenarios in bio-ethanol supply chain (Chen and Fan, 2012).

Table 2- 3: HAZOP worksheet for Node 1

Node 1:	**Biomass supply**				
Node description:	**Supplement of biomass from plantation and process waste to respective pretreatment and process for production of downstream product**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
Quantity	More	1. Peak season of plantation	1.1. More biomass generation resulting in potential underutilisation of biomass 1.2. Potential environmental pollution due to improper biomass waste management	1.1.1. Seasonal biomass problems are evaluated by researchers, but less has studied impact of over-supply. 1.1.2. See Section 2.2.2.1	1) Consideration of alternative application for excessive biomass.
		2. New plantation field	2.1. More biomass within the system resulting in potential underutilisation of biomass 2.2. Potential environmental pollution due to improper biomass waste management 2.3. Lower biomass market value due to more supply available	2.1.1. Fluctuation/uncertainty of biomass resource is considered in existing model (see Section 2.2.2.1)	2) Consider to develop a model to evaluate/forecast biomass market value based on fluctuation of biomass availability
		3. Establish/introduce/discovery of new biomass species in the system	3.1. Potential underutilisation of respective biomass due to lack of knowledge in respective biomass	3.1.1. Less studies have been conducted to include new/underutilised	3) Consider to develop new method to include new species or

Table 2-3: HAZOP worksheet for Node 1 (continue)

Node 1:	**Biomass supply**				
Node description:	**Supplement of biomass from plantation and process waste to respective pretreatment and process for production of downstream product**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
			application	biomass into existing model	underutilised biomass into existing system
		4. Introduction of new harvesting method or improvement of existing harvesting method	4.1. Increase efficiency of biomass harvesting leading to potential higher biomass supply and cost reduction 4.2. No significant hazard to overall biomass supply chain	4.1.1. Harvesting optimisation including harvesting process and equipment were conducted (see Section 2.2.2.2)	No recommendation required
	Less/No	1. Low season of plantation	1.1. Less biomass availability for raw material supply resulting in lower production rate of downstream product	1.1.1. Many works have been conducted to consider biomass uncertainty including seasonal biomass (see Section 2.2.2.1) 1.1.2. Biomass storage allows some buffering period between seasons (see	No recommendation required

Table 2-3: HAZOP worksheet for Node 1 (continue)

Node 1:	**Biomass supply**				
Node description:	**Supplement of biomass from plantation and process waste to respective pretreatment and process for production of downstream product**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
				Section 2.2.2.4)	
		2. Lower biomass generation rate (e.g. Replantation, weather impact)	2.1. Less biomass availability for raw material supply resulting in lower production rate of downstream product	2.1.1. Consideration of uncertainty in biomass supply (see Section 2.2.2.1)	4) Consider to integrate live-time weather condition into biomass supply chain management
		3. Less efficiency in biomass harvesting (e.g. due to weather condition and labour)	3.1. Unable to fulfil downstream requirement at process plant leading to insufficient production rate 3.2. Lower quality of biomass (such as higher moisture content) leading to higher pretreatment cost 3.3. Higher overall production cost leading to potential infeasibility in overall biomass system	3.1.1. Various harvesting process, management and equipment are considered in optimisation model (see Section 2.2.2.2)	Refer to recommendation (4): Consider to integrate live time weather condition into biomass supply chain

Table 2-3: HAZOP worksheet for Node 1 (continue)

Node 1:	**Biomass supply**				
Node description:	**Supplement of biomass from plantation and process waste to respective pretreatment and process for production of downstream product**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
		4. Equipment malfunction in harvesting process	4.1. Unable to harvest biomass leading to less biomass supply impacting downstream process such as lower production rate	4.1.1. Various harvesting process, management and equipment are considered in optimisation model (see Section 2.2.2.2) 4.1.2. Sufficient storage of biomass in preproduction stage to minimise process fluctuation due to instability of biomass supplement (see Section 2.2.2.4)	No recommendation required
Quality	More/ Higher	1. Higher quality of biomass (such as good weather resulting less moisture	1.1. Higher quality of biomass resulting less pretreatment required and higher efficiency in downstream	No safeguard required	No recommendation required

Table 2-3: HAZOP worksheet for Node 1 (continue)

Node 1:	**Biomass supply**				
Node description:	**Supplement of biomass from plantation and process waste to respective pretreatment and process for production of downstream product**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
		biomass, less contaminated biomass)	processes 1.2. No significant process hazard and consequence		
	Less/ Lower	2. Bad weather (raining season)	2.1. Higher moisture content in biomass encourage organic contamination 2.2. Higher transportation cost due to the additional weight of water content 2.3. Biomass element and nutrient loss due to rain	1.1.1. Consideration of pretreatment process in supply chain model (see Section 2.2.2.3) 2.2.1. On-site pretreatment (drying) to optimise logistic cost 2.2.2. Feasibility study of biomass transportation (see Section 2.2.2.6)	5) Develop systematic biomass evaluation approach to ensure consistency of biomass quality upon received
Logistic/ Transportation	More	1. High biomass collection cost (due to scattered biomass location or relatively low density of	1.1. High biomass supply cost leading to infeasible biomass application 1.2. Unsystematic biomass collection resulting in high transportation cost	1.1.1. Feasibility study of biomass transportation (see Section 2.2.2.6) 1.2.1. Geographical	6) Consider to develop a systematic approach to identify potential application of all

Table 2-3: HAZOP worksheet for Node 1 (continue)

Node 1:	**Biomass supply**				
Node description:	**Supplement of biomass from plantation and process waste to respective pretreatment and process for production of downstream product**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
		biomass)	1.3. Potential ignorance of valuable biomass at varies different location to minimise logistic cost	Information System guided model to optimise logistic management	biomasses within the system
	Less/No	No cause identified	No consequence	No safeguard required	No recommendation required
Market Value/Cost	More	1. Higher raw biomass cost (due to less supply or less competitive market)	1.1. Higher overall production cost leading to potential infeasibility in overall biomass system	1.1.1. Consideration of uncertainties of biomass availability and market demand (see Section 2.2.2.1)	No recommendation required
		2. Higher labour cost	2.1. Higher production cost resulting in potential infeasible in biomass industry	2.1.1. Consideration of uncertainties of biomass collection and harvesting handling cost (see Section 2.2.2.1 and 2.2.2.2)	No recommendation required

Table 2-3: HAZOP worksheet for Node 1 (continue)

Node 1:	**Biomass supply**				
Node description:	**Supplement of biomass from plantation and process waste to respective pretreatment and process for production of downstream product**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
	Less	1. Lower raw biomass cost (due to more supply or high competitive market)	1.1. Lower overall production cost potentially enhances overall biomass system performance 1.2. No significant impact to process hazard	No safeguard required	No recommendation required

Table 2- 4: HAZOP worksheet for Node 2

Node 2:	**Biomass processing plant**				
Node description:	**Process raw biomass via pretreatment and core process reaction to produce downstream product or energy**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
Quantity	More	1. Over accumulation of biomass in storage due to improper supply management	1.1. Degradation of biomass due to prolong storage affecting pretreatment or core processes resulting in higher production cost 1.2. Contamination of biomass leading to potential environmental pollution	1.1.1. On-site pretreatment or pretreatment before storage to prolong biomass storage time 1.1.2. Biomass storage and scheduling optimisation (see Section 2.2.2.4) 1.2.1. Consideration of environmental impact in biomass supply chain optimisation (see Sections 2.2.2.5 and 2.2.2.6)	No recommendation required
		2. More biomass waste produced from process plant	2.1. Increase of process waste/biomass resulting in underutilisation biomass 2.2. Higher cost in waste management	2.2.1. Consideration of environmental impact in biomass supply chain optimisation (see	7) Develop approach to evaluate potential utilisation of biomass process waste

Table 2-4: HAZOP worksheet for Node 2 (continue)

Node 2:	**Biomass processing plant**				
Node description:	**Process raw biomass via pretreatment and core process reaction to produce downstream product or energy**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
				Section 2.2.2.5 and 2.2.2.6)	
	Less/No	1. Low biomass stock in storage due to less raw biomass supply upstream	1.1. Low/No supply to processes leading to inefficient production and potential stop of production	1.1.1. Consideration of biomass availability uncertainties (see Section 2.2.2.1) 1.1.2. Scheduling of biomass logistic and storage (see Section 2.2.2.4) 1.1.3. Switch over to alternative biomass as feedstock (with different operating parameters)	8) Consider to develop systematic approach for alternative biomass feedstock selection without major impact to operating conditions
Quality	More/ Higher	1. Unnecessary biomass pretreatment	1.1. Unnecessary higher cost of pretreatment, but no major impact to biomass processes	No safeguard required	No recommendation required
	Less/ Lower	1. Inefficiency or	1.1. Lower quality of biomass into core	1.1.1. Consideration of	No recommendation

Table 2-4: HAZOP worksheet for Node 2 (continue)

Node 2:	**Biomass processing plant**				
Node description:	**Process raw biomass via pretreatment and core process reaction to produce downstream product or energy**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
		malfunction of pretreatment unit	processing plant resulting in potential lower efficiency in reaction leading to low product quality 1.2. Unable to achieve standard product quality and demand	multiple process plant as contingency plan to fulfil market demand 1.1.2. Standard operating procedure and regular maintenance	required
		2. Inefficiency or malfunction of processing equipments	2.1. Lower efficiency in process reaction leading to low product quality 2.2. Unable to achieve standard product quality and demand	2.1.1. Consideration of multiple process plant as contingency plan to fulfil market demand 2.1.2. Standard operating procedure and regular maintenance	No recommendation required
Logistic/ Transportation	More	1. Location of process plant (e.g. far from resource point or scattered distribution)	1.1. High transportation cost resulting in high production cost and potentially leading to infeasible production	1.1.1. Optimisation of process plant location (see Section 2.2.2.5)	No recommendation required

Table 2-4: HAZOP worksheet for Node 2 (continue)

Node 2:	**Biomass processing plant**				
Node description:	**Process raw biomass via pretreatment and core process reaction to produce downstream product or energy**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
	Less/No	1. No cause identified	No consequence	No safeguard required	No recommendation required
Market value/Cost	More	1. Higher labour or process chemical or utility cost	1.1. Higher production cost resulting in potential infeasible in biomass industry	1.1.1. Consideration of operating cost uncertainty (see Section 2.2.2.1)	No recommendation required
		2. Higher biomass supply cost due to low biomass availability	2.1. Higher production cost resulting in potential infeasible in biomass industry	2.1.1. Consideration of biomass availability uncertainty (see Section 2.2.2.1) 2.1.2. Biomass storage and scheduling optimisation (see Sections 2.2.2.4 and 2.2.2.6)	No recommendation required
	Less	1. No cause identified	No consequence	No safeguard required	No recommendation required

Table 2- 5: HAZOP worksheet for Node 3

Node 3:	**Transportation and logistics of biomass and product**				
Node description:	**Delivery of raw biomasses to process plant and products to market demand location**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
Quantity	More	1. Higher transportation capacity	1.1. Lower transportation cost, no significant process hazard to overall supply chain	No safeguard required	No recommendation required
	Less/No	1. Transporting less biomass than the maximum capacity of transportation vehicle	1.1. Potential not optimum biomass to fuel ratio resulting in higher transportation cost per unit of biomass	1.1.1. Logistic management by optimisation of multiple type of transportation mode/vehicle (see Section 2.2.2.6)	No recommendation required
Quality	More/ Higher	1. Better efficiency of transportation	1.1. Lower transportation cost, no significant process hazard to overall supply chain	No safeguard required	No recommendation required
	Less/ Lower	1. Lower efficiency of transportation	1.1. Higher cost of logistic leading to potential infeasible biomass	2.1.1. See Section 2.2.2.6	No recommendation required
Logistic/ Transportation	More	1. No cause identified	No consequence	No safeguard required	No recommendation required
	Less/No	1. Limitation of transportation due to	1.1. Unable to deliver biomass or product to destination on time	1.1.1. Consideration of alternative route as	No recommendation required

Table 2-5: HAZOP worksheet for Node 3 (continue)

Node 3:	**Transportation and logistics of biomass and product**				
Node description:	**Delivery of raw biomasses to process plant and products to market demand location**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
		road condition	resulting in insufficient biomass feedstock in process plant or delay of product delivery	contingency plan for unexpected road condition 1.1.2. Geographical Information System assisted model for optimum transportation route (see Section 2.2.2.6)	
		2. Limitation of transportation due to weather (e.g. flood which impacting large area)	2.1. Unable to deliver biomass or product to destination on time resulting in insufficient biomass feedstock in process plant or delay of product delivery 2.2. Lower biomass quality upon delivery (such as due to rain)	2.1.1. Consideration of alternative route as contingency plan for unexpected road condition 2.1.2. Geographical Information System assisted model for	Refer to recommendation (5): Develop systematic biomass evaluation approach consistency of quality upon received

Table 2-5: HAZOP worksheet for Node 3 (continue)

Node 3:	**Transportation and logistics of biomass and product**				
Node description:	**Delivery of raw biomasses to process plant and products to market demand location**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
				optimum transportation route (see Section 2.2.2.6) 2.2.1. Biomass supply chain optimisation with consideration of pretreatment (see Section 2.2.2.3)	
Market value/Cost	More	1. Higher transportation fuel or labour cost	1.1. Higher production cost resulting in potential infeasible in biomass industry	1.1.1. Consideration of uncertainty in fuel and labour cost (see Section 2.2.2.1)	No recommendation required
	Less	1. Lower transportation fuel or labour cost	1.1. Lower cost in biomass implementation and lower downstream production cost. 1.2. No significant process hazard to overall biomass supply chain	No safeguard required	No recommendation required

Table 2- 6: HAZOP worksheet for Node 4

Node 4:	**Market demand**				
Node description:	**Biomass downstream product demand**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
Quantity	More	1. Higher market demand for downstream product	1.1. Production at maximum rate due to high market value and demand, however, production rate is limited by the total amount of raw biomass available at upstream for respective process technology 1.2. Higher product value due to inadequacy in the supply	1.1.1. Consideration of dedicated alternative biomass feedstock to temporarily increase production (only for process tested with multiple type of biomass feedstock, operating condition might differ based on feedstock type) 1.2.1. Consideration of product/market uncertainty (see Section 2.2.2.1)	9) Consider to develop approach to increase biomass feedstock selection for process technology in order to increase production capacity and flexibility.
	Less/No	1. Lower product demand or competitive market	1.1. Lower production rate potentially impacts upstream raw biomass	1.2.1. Optimisation of biomass storage and scheduling	Refer to recommendation

Table 2-6: HAZOP worksheet for Node 4 (continue)

Node 4:	**Market demand**				
Node description:	**Biomass downstream product demand**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
			handling and supplement 1.2. Potential accumulation of biomass upstream due to low biomass demand leading to potential environmental pollution and higher biomass waste management cost 1.3. Lower selling value of upstream biomass	(see Sections 2.2.2.3 and 2.2.2.4) 1.3.1. Consideration of product/market uncertainty (see Section 2.2.2.1)	(1): Consideration of alternative application for excessive biomass. Refer to recommendation (7): Develop approach to evaluate potential utilisation of biomass process waste
Quality	More/ Higher	1. Market demand for higher quality of product	1. Existing process technologies unable to fulfilled the requirement without major process modifications	No specific safeguard identified	10) Consider to develop a model to evaluate/forecast product market value and quality requirement
	Less/ Lower	1. Market demand for	1. Existing process technologies	No specific safeguard identified	Refer to recommendation

Table 2-6: HAZOP worksheet for Node 4 (continue)

Node 4:	**Market demand**				
Node description:	**Biomass downstream product demand**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
		lower quality of product	unable to fulfilled the requirement without major process modifications		(10): Consider to develop a model to evaluate/forecast product market value and quality requirement
Logistic/ Transportation	More	No cause identified	No consequence	No safeguard required	No recommendation required
	Less/No	No cause identified	No consequence	No safeguard required	No recommendation required
Market value/Cost	More	1. Higher market value of product	1. Increase overall profit of the system, no significant process hazard to overall biomass supply chain	No safeguard required	No recommendation required
	Less	1. Lower market value of product	1. Lower overall profit resulting to potential negative net profit	No specific safeguard identified	Refer to recommendation (10):

Table 2-6: HAZOP worksheet for Node 4 (continue)

Node 4:	**Market demand**				
Node description:	**Biomass downstream product demand**				
Deviation	**Guideword**	**Causes**	**Consequences**	**Safeguards/Current solution**	**Recommendations**
			leading to infeasibility of the system		Consider to develop a model to evaluate/forecast product market value and quality requirement

2.2.2.2. Harvesting:

Out of numerous harvesting methods, one-pass harvest system is one of the economically promising approaches (Walsh and Strandgard, 2014). This approach integrates underutilised biomass such as woody biomass or forest residue with higher value plantation resources within the harvest site, minimising overall operational and management cost. However, harvesting is highly dependent on the system used, site condition and type of biomass. For example, collection of woody biomass is rather complex in Australia due to the scatter over harvest site; while in contrast, woody biomass concentrated along side of road or central processing yards in New Zealand (Walsh and Strandgard, 2014). Various harvesting, handling and processing equipment were considered as part of the supply chain model proposed by Hall et al. (2001) for optimum implementation. Sokhansanj et al. (2006) developed a model to predict size and number of equipment according to the harvest rate. The model also considered demand of bio-refinery and biomass delivery cost.

2.2.2.3. Pretreatment processes:

Pretreatment is a process to convert raw biomass into higher value material, in terms of higher energy density, removal of contamination, preserve biomass for longer storage period, or increase ease of handling, storage, transportation and reduces associated cost (Mafakheri and Nasiri, 2014). Pretreatments include drying and torrefaction, pelletisation, shredding, grinding, chopping and carbonisation are used in biomass energy industry (Uslu et al., 2008). However, not all biomass should go through pretreatment process. For instance, in the case of palletising log biomass, preserving particular amount of moisture content in log is crucial to ensure good quality in pellet strength (Lehtikangas, 2001). Thus in this case, drying process can be avoided or need to be controlled to avoid over-dried the biomass. Consideration of several small pretreatment units in biomass supply chain model proposed by Carolan et al. (2007) achieved feasible economic scale while minimising transportation and storage cost by decentralising pretreatment activities.

2.2.2.4. Biomass storage:

Many researchers have conducted studies in biomass storage which focused on the analysis of storage location with respect to the transportation cost, storage capacity, and scheduling (Mafakheri and Nasiri, 2014). For example, Nilsson and Hansson (2001) studied intermediate storage locations for biomass power plant supply chain network, while Huisman et al. (1997) studied biomass on-field storage for cost analysis. Eksioğlu and Petrolia (n.d.) investigated the meeting point of different transportation mode and proposed optimum biomass storage and distribution strategy. A batch process scheduling framework was developed by Dunnett et al. (2007) with the consideration of biomass harvesting and biomass consumption.

2.2.2.5. Biomass conversion processes:

Numerous studies were conducted to analyses the variables of conversion process plant within biomass supply chain, such as optimal process plant location within respective biomass system. Vera et al. (2010) developed a model to identify best location for biomass power plant to maximise profit. Velazquez-Marti and Fernandez-Gonzalez (2010) exploited Geographical Information System (GIS) approach into selection of bioenergy process plant location to minimise overall cost in the biomass system. Others have been conducting research on analysing and optimising multiple process pathways. Cameron et al. (2007) evaluated and compared biomass gasification and combustion in a cost minimisation model. Fromboo et al. (2009) conducted research in GIS-based Environmental Decision Support System to develop decision and environmental model for biomass-based energy production over a long term period. The model includes conversion processes such as pyrolysis, gasification, and combustion, as well as considering the plant location and harvested biomass. Bai et al. (2011) worked on model for planning of biofuel refinery locations to minimise total cost with respect to refinery investment and logistic cost. Researchers also developed optimisation model with multi biomass type of feedstock. For example, Zhu and Yao (2011) developed a model to consider switchgrass, corn stalk and wheat straw as potential feedstock for biofuel production. The model determines optimal solution for the system in line with seasonal availability of biomass to smoothen the biofuel production throughout the year. However, no mixing of multiple biomasses feedstock is considered. The process is operated with one biomass at a time. Different biomass feedstock or mixture of biomass will give different impact to overall process efficiency, yield and operating parameters. Meyer et al. (2015) constructed a biomass supply chain model to maximise net energy output of upstream biomass system including conversion facilities, transportation and handling, harvesting, and pretreatment. However, as part of the operational constraint, the proposed biomass supply chain model has the restriction such that each type of conversion facility can only accept respective type of biomass.

2.2.2.6. Biomass transportation and logistics:

Hall et al. (2001) considered multiple type of transport vehicle based on the load space, weight, maximum payload allowable in transportation regulation and transportation cost. GIS model was used to estimate the transportation cost. Graham et al. (2000) used GIS to estimate biomass transportation cost and environmental impact cost in United State. GIS was applied to determine optimum biomass supply network subject to various scenarios including biomass availability and feasibility of delivery (Perpiná et al., 2009). Besides, centralised and decentralised biomass logistic was studied to minimise biomass supply chain cost (Gronalt and Rauch, 2007). Similarly, Ng and Lam (2014) introduced functional clustering technique to maximise economic potential of each biomass industry cluster. The model proposes possible biomass processing hub to optimise the overall biomass logistic performance. Truck scheduling was conducted by Ravula et al. (2008) with comparison of overall minimising transport time policy and sector based transportation policy. Life cycle analysis concept was applied into biomass transportation to assess emissions such as NOx and carbon dioxide CO_2 to environment Forsberg (2000).

2.3 Discussion

Based on the HAZOP approach, the current state of biomass supply chain optimisation development is well evaluated. Although researchers have conducted numerous studies and developed biomass supply chain models to optimise the system, yet the study identified potential improvement of the system. Table 2-7 summaries all recommendations suggested in the HAZOP assessment.

Table 2- 7: HAZOP recommendations

No.	Recommendations
1	Consideration of alternative application for excessive biomass
2	Consider to develop a model to evaluate/forecast biomass market value based on fluctuation of biomass availability
3	Consider to develop new method to include new species or underutilised biomass into existing system
4	Consider to integrate live-time weather condition into biomass supply chain management
5	Consider to develop systematic biomass evaluation approach to ensure consistency of biomass quality upon received
6	Consider to develop a systematic approach to identify potential application of all biomasses within the system
7	Consider to develop approach to evaluate potential utilisation of biomass process waste
8	Consider to develop systematic approach for alternative biomass feedstock selection without major impact to operating conditions
9	Consider to develop approach to increase biomass feedstock selection for process technology in order to increase production capacity and flexibility
10	Consider to develop a model to evaluate/forecast product market value and quality requirement

From the list of recommendations, various research gaps were identified ranging from integration of biomass resources and conversion processes, forecasting uncertainties, and waste minimisation and reutilisation. Each recommendation is suggested based on the cause and consequence analysis from HAZOP study. Upon examination and breakdown, seven out of ten recommendations are related to integration between biomass resources and conversion processes which suggested that many improvements can be done in this area. One of the potential main issues is due to isolated biomass development. As each biomass has its unique properties and availability at dedicated location, development of biomasses are usually independent from each region. Researchers normally work on biomasses that are available in respective region in order to improve the feasibility of implementation. For example, palm oil biomasses are the main research topic in Malaysia due to the high accessibility to palm oil plantation. Consequently, this resulted isolation of development such as in laboratory experiment where researches on conversion technology only focused in particular species of biomass (palm biomass in the case of Malaysia), or biomass supply chain optimisation model developed to solve specific scenario within the regional system only. In addition, repetitive research and development are normally required to verify each case, and hence limits the global implementation of biomass integration knowledge. Implementation of well developed technology is not possible by using different biomass feedstock or in different region without proper experimental studies. This is due to current studies on biomass technology are normally constraint to specific biomass species originates from a specific location. Technically, biomass technology is not developed to tolerate different biomass species or from different origin. Thus this limits the flexibility of feedstock selection and integration, resulting in non-mainstream biomass species are normally being ignored and unable to implement into the system due to lack of study. For example, Lu et al. (2012) shows that every kg of corn cob is able to produce 30.46g of hydrogen via the proposed operating conditions. However, in the case of corn cob is unavailable within a region or a period of time, this technology is no longer practical to be applied. Utilising alternative biomass as feedstock is also not feasible as the technology performance is yet to be verified when using alternative feedstock.

Thus, these explained the gaps suggested in Recommendations (1), (3), (6), (8), and (9), where systematic platforms should be considered to integrate multiple biomasses to various conversion processes. Ideally development of each biomass conversion technology should applicable to various types of biomass species. For organic resource or biomass, their properties fluctuate depending on seasons, weather, location, and handling. Thus, a systematic platform to evaluate biomass quality is essential to ensure consistency as per Recommendation (5). Several approaches are currently available to classify biomass properties, such as element characteristic. However, it is critical to identify the impacts of different feedstock properties to the process outcome. For example, Mohammed et al. (2011) suggested that biomass with moisture content of more than 50 wt% is not feasible in combustion process. Biomass properties have a very high potential to act as a platform to categorize biomass applications.

The HAZOP study also identified issue of potential biomass underutilisation. Depending on the properties of respective biomass and process waste, the materials have potential for reutilisation. For example, Miguel et al. (2012) suggested that particle from biomass gasification waste has high heating value and has the potential as a co-fired fuel. Thus, process waste from biomass conversion technology should be taken into consideration to optimise resource utilisation and minimise waste management effort. This also applies to underutilisation of potential biomass within the system as per Recommendations (3) and (7). In this context, underutilised biomass is refers to non-mainstream biomass species that are available within the system. For example, the current developments highly focus on mainstream biomass such as palm biomass. However, multiple small scale biomasses such as forestry biomass, food waste, fruit shell type biomass (such as coconut shell, and durian shell- a tropical fruit biomass) have less attention in research and utilisation. Noted that combination of numerous small scale biomasses might have the potential to form a sustainable biomass supply chain system, or as alternative feedstock for mainstream biomass processes.

Another research gaps that could be considered in biomass supply chain model is forecasting uncertainty such as weather condition, road conditions, biomass availability and market demand. Current approaches to handle uncertainty are toward scenario based problem solving and propose alternative solution. Forecasting future problem enhances supply chain management by taking prevention action one step before the problem occurs. For example, integrates weather forecast in handling of biomass transportation can minimises exposure of biomass to rain. Live-time or forecasting road condition enables analysis of supply chain pathways to avoid high traffic route to minimise logistic cost and ensure on-time delivery. Integration of relation between multiple uncertainties also helps to simplify the supply chain management. For example, forecasting biomass availability and product market demand to determine fluctuation in biomass market value. This provides a good platform to manage biomass applications.

From the discussion, HAZOP approach benefits the review of biomass supply chain optimisation model by analysing each stage of the process with guided direction. This approach minimised the chances of problem ignorance thus provides a high level and detail analysis. In addition, the proposed general HAZOP methodology for literature review can also be implemented in different research area to ensure consistency and good quality.

2.4 Solutions for research gaps

Based on the critical review on biomass supply chain optimisation models above, the analysis suggested a number of potential research gaps. Most of the identified gaps are related to the lack of alternative biomass integration into existing supply chain network, thus leading to underutilisation of biomasses. The findings are in parallel with the problem statements in Chapter 1. In order to handle this issue, research methodology is proposed to introduce a novel approach to improve the existing biomass supply chain network management.

2.4.1. Propose novel integration approach to consider alternative/underutilised biomass into existing supply chain network

In order to integrate alternative biomasses into the existing biomass supply chain optimisation models, the first step is to introduce a common platform to consider all potential biomass available within the system. Conventionally, biomass technology feedstock selection is based on biomass species which limits the selection of other biomass species. This research introduced a classification platform to evaluate biomass application based on their properties. In order to define the selection factors, biomass technologies available in literature will be evaluated. Then, a constructive platform to link multiple biomass resources to respective technologies is introduced. Figure 2-2 presented the general procedure and the detail description is available in Chapter 3.

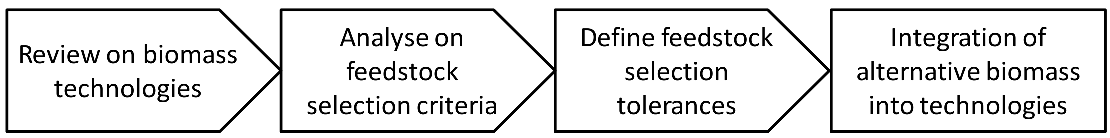


Figure 2- 2: Research methodology to introduce integration approach to consider alternative biomasses

2.4.2. Concept verification

Due to the novelty of the proposed approach, this research will also focus on concept verification to ensure applicability of the approach. Two methods of verification are suggested, a literature based approach and an experiment based approach. In the literature based concept verification, recent biomass technologies available from literature are compiled and analyse. Although the research objectives in literature are different, this scope verified the concept via the reported experiment data. This will also act as a determining factor to evaluate if the proposed approach can be applied into existing technologies. The second approach of concept verification is via experiment. Collaborator will be engaged to test the concept of integrating multiple biomasses into the technology. The main objective is to evaluate the process performance fluctuation based on different feedstock while the operating conditions remaining constant.

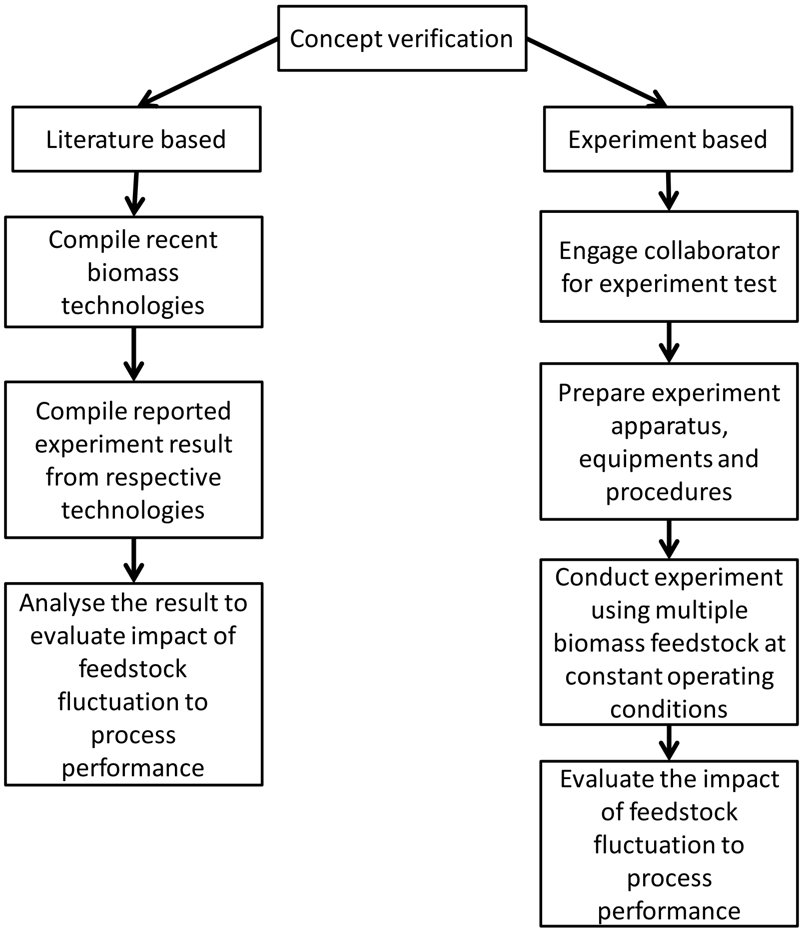


Figure 2- 3: Research methodology to verify proposed integration approach

2.4.3. Construction of biomass supply chain model

In order to enable consideration of alternative/underutilised biomass into the supply chain optimisation model, the proposed concept is required to integrate into the mathematical formulation. The methodology of this work is to compare the proposed model with conventional supply chain optimisation approach via demonstration case studies. The case studies will focus on regional biomass system. The mathematical models will be solved using General Algebraic Modelling System (GAMS) software.

2.5 Conclusions

Current biomass supply chain optimisation models are evaluated via a systematic HAZOP assessment approach. Upon investigation, various biomass supply chain process hazards are identified. Literature review shows that numerous studies have conducted to rectify the hazards, thus minimising the impact to the overall supply chain. Nevertheless, several inadequacy of protection are identified and recommended as potential future work to fill in the current research gaps. For example, the lack of flexibility in alternative biomass integration into existing conversion processes. Over-isolation of biomass development limits the exploration of alternative biomass species thus restricts the overall performance of biomass system. Integration of alternative biomass as feedstock, biomass process waste and underutilised biomass are considered in order to improve overall biomass utilisation and performance. In addition, improvement in forecasting uncertainties can be considered in future biomass supply chain development. In conclusion, HAZOP approach has successfully assists the review of biomass supply chain optimisation model. The proposed methodology is capable to be applied in other field of research for a high level literature review. Lastly, this HAZOP based research methodology is proposed as a guideline to achieve the targeted outcome; which is to introduce and to verify a novel integration approach that considered alternative/underutilised biomass in existing biomass supply chain optimisation model.

Chapter 3:
ELEMENT TARGETING APPROACH

Several potential improvements from existing biomass supply chain were suggested as per literature review in Chapter 2. In this chapter, analysis is conducted on the recommendations and a novel approach to improve the biomass supply chain system is introduced. A systematic biomass classification and targeting approach is proposed to integrate alternative biomass into the existing biomass supply chain network without major modification of the process technologies. The approach is suggested to be user-friendly such that it is applicable for various biomass process technologies and suitable for different regional areas.

3.1 Analysis on literature review recommendations: Fill in current research gaps

Based on the proposed literature review (HAZOP recommendations) in Chapter 2, a number of biomass supply chain management issues were highlighted. Upon preliminary analysis, some of the proposed recommendations are correlated with each other. For instance, Recommendations 1, 3, 6, and 7 highlighted the issue of biomass and process waste underutilisation within the system. Recommendations 8 and 9 addressed the criticality to maintain the normal operation conditions or to have minimum design modification. Recommendation 5 suggested an evaluation approach to ensure biomass feedstock quality. In order to deal with these issues, the proposed approach is required to act as a platform to evaluate the biomass quality upon receiving as feedstock and enable integration of underutilised or alternative biomass without compromising the normal process operations. This is the ultimate objective of this research. On the other hand, Recommendation 10 to develop market demand prediction model will not be covered in this research due to it is not the main focus of this work. This scope can be proposed as future work to strengthen the supply chain model based on market fluctuations.

Figure 3.1 shows the generic biomass supply chain optimisation superstructure, starting from biomass resources to process technology to market demand. In the biomass supply chain management, each available biomass species is assigned to a dedicated biomass process technology based on the technology feedstock requirement derived from experimental work. For example, Ge et al. (2016) reported that the proposed biomass gasification reactor with chemical looping technology produces maximum syngas yield of 0.64Nm^3/kg at 850°C. The biomass feedstock used in the study consisted of rice husk from Jiangsu, China. No research has been conducted on alternative biomass species (such as coconut shell) to investigate their performance in the proposed technology. When reflect to biomass supply chain network, this creates limitations in biomass supply chain management where only rice husk fits the feedstock requirement of the technology. Thus the technology is only feasible to implement in regions with rice husk resources. Additional laboratory work to study the impact of integration of alternative biomass species into the system is required. Besides, fluctuation of rice husk properties from different region may affect the overall process performance.

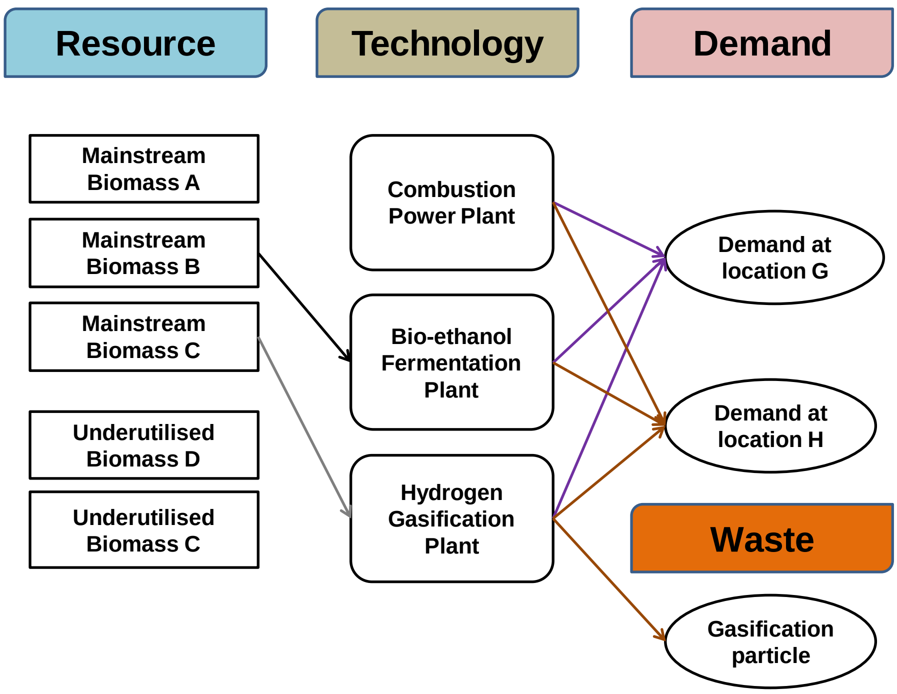


Figure 3- 1: Generic biomass supply chain optimisation superstructure

In order to achieve the objective of the research, a new classification platform to integrate alternative biomasses into existing process technology is proposed as shown in Figure 3-2. The main idea is to break through the limitation in biomass feedstock selection, where currently biomass technology feedstock is selected based on biomass species. The fundamental of the classification platform is to categorize each biomass, including underutilised biomass into their respective properties and to evaluate potential application of each biomass into various process technologies. This provides a platform to integrate various biomass species into the supply chain network where each biomass is evaluated and assigned to respective process technology based on the feedstock acceptance criteria. The proposed approach is targeted to rectify Recommendations 1, 3, 5, 6, and 7 stated above which are related to exploitation of underutilised biomass. Detail methodology is described in next section.

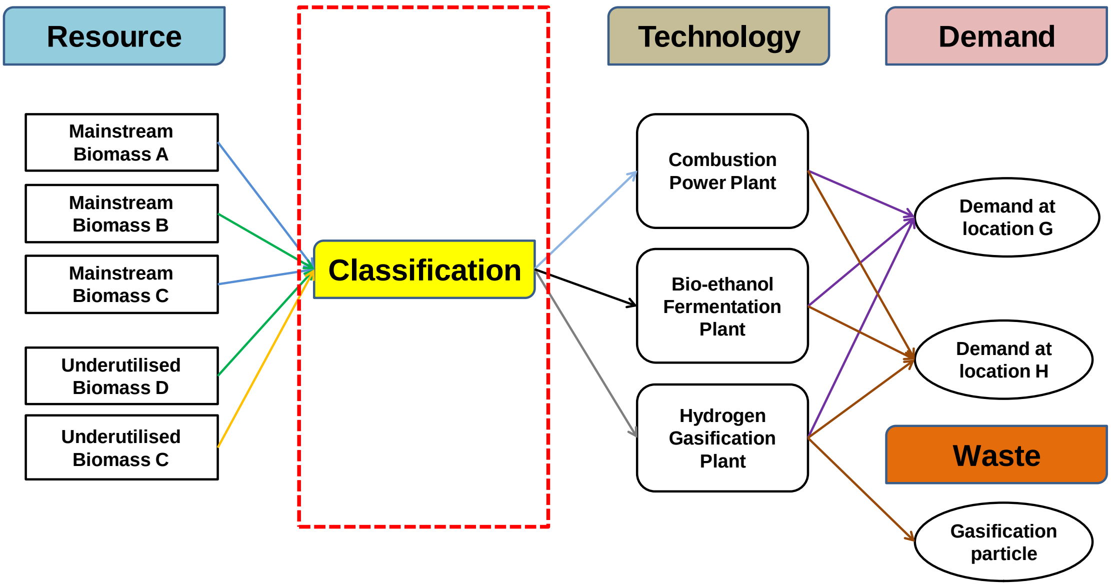


Figure 3- 2: Introduction of classification platform to integrate biomass and process technology

3.2 Review on biomass technologies

In order to construct a common platform for all biomass species, biomass technologies are reviewed. Generally, biomass technologies can be categorized into three type, physical (pelletising, shredding), chemical/thermochemical (pyrolysis, gasificaion) and biological (fermentation). Although biomass properties such as moisture content plays as one of the critical criteria in biomass physical conversion technologies (Lehtikangas, 2001), however, the main challenge in biomass industry lays in the chemical and biological conversion technologies. Thus, the main objective in this work is to identify feedstock selection criteria and the similarity between biomass technologies (chemical and biological). The review provides a good analysis to propose a classification platform as shown in Figure 3-2. Three general biomass technologies were evaluated, namely pyrolysis, gasification, and hydrolysis and fermentation.

3.2.1 Biomass pyrolysis

Pyrolysis is a thermal chemical decomposition of organic material into bio-oil, syngas and charcoal with the absence of oxygen. Depending on the operating temperature, production yield of oil, gas and charcoal varies. Operating temperature of pyrolysis ranged from 350°C to 550°C (Mohammed et al., 2011). Slow pyrolysis with high temperature, low heating rate and long gas resistance time tends to produce more charcoal; while fast pyrolysis at very high temperature, short vapour resistance time, fine biomass feedstock, and rapid cooling of pyrolysis vapour produces more bio-oil. Many research works have been conducted to improve pyrolysis process to enhance production yield and overall efficiency. For example, Mushtaq et al. (2014) reviewed the pyrolysis of coal and biomass with assistance of microwave. Microwave heating enhance heating efficiency of coal or biomass with microwave absorber and improve the fuel quality.

Apart from improving efficiency, several researches have also evaluated the impact of pyrolysis outputs with respect to element characteristic of biomass feedstock. Azargohar et al. (2014) studied the chemical and structural properties of biomass and their impact in fast pyrolysis to produce bio-char. The study proposed that biomass with lower hydrogen over oxygen ratio (H/C) and oxygen over carbon ratio (O/C), and ash content is more suitable as feedstock for activated carbon production. Giudicianni et al. (2014) conducted research on the relation of cellulose, hemicellulose and lignin to Arundo donax steam assisted pyrolysis. The result shows that more lignin content increases yield of bio-oil and reduce yield of char. Present of steam promotes gasification thus reducing char yield. Phan et al. (2014) evaluated bio-oil production from Vietnamese biomasses via fast pyrolysis. The study concluded that bigger biomass feedstock size decreases bio-oil yield. Bagasse yielded highest bio-oil production at 67.22% with lowest water content of 17% in bio-oil.

From element characteristic comparison, bagasse has highest combustible, cellulose, and lignin content, and lowest ash content.

Based on literature, element characteristics of biomass and production yield of pyrolysis are closely related. Element such as H/C and O/C ratio, cellulose, hemicellulose, lignin, ash, and feedstock size are affecting the product output from pyrolysis. With more detail research, this information can be used as a guideline to predict pyrolysis process outcomes based on the feedstock properties.

3.2.2 Biomass gasification

Gasification is a process that converts biomass into combustible gases mixtures such as syngas and light hydrocarbon gases at temperature range around 700°C to 1000°C with the present of controlled amount of oxidation agent (Mohammed et al., 2011). It is a very complex process involving water evaporation, volatiles pyrolysis, combustion, volatiles gasification, and char gasification, with char gasification as controlling step due to the slower reaction rate (Dupont et al., 2011). Oxidation agent can be air, hydrogen, steam, CO_2 or mixture of respective fluid. Using air as oxidation agent reduces syngas heat value (Wang et al., 2008). Pure oxygen as oxidation agent enhances syngas heat value; however it raises issue in terms of high cost and operation safety (Ni et al., 2006). Similarly, steam as oxidation agent increases heat value and hydrogen yield, but requires additional cost for heating facility for steam production (Rapagna et al., 2000). Using carbon dioxide is one of the promising oxidation agents due to its presence in syngas (Gil et al., 1999).

Song et al. (2013) evaluated element utilisation of carbon, hydrogen and oxygen in a co-gasification system of coal and biomass feedstock. The study shows that temperature of gasification and steam flowrate are one of the affecting factors in gasification. Several researchers have conducted study on inorganic element in biomass gasification, in particular aspects related to gasification of ash. Dupont et al. (2011) presented study on correlation between inorganic elements of woody biomass and char steam gasification kinetics. Liao et al. (2007) characterised inorganic element such as As, Al, Ca, Cd, Cr, Cu, K, Mg, Na, Ni, Pb, and Ti from circulating fluidized bed wood gasification power plant. Biäsing et al. (2013) traced inorganic elements in gasification with respect to biomass pellet sizes. In biomass gasification, feedstock with lower hydrogen, nitrogen and sulphur content produces less gaseous pollutant such as NOx and SOx (Miguel et al., 2012). Drier biomass feedstock yields lower hydrogen gas while higher H/C ratio of feedstock increases hydrogen gas production (Vitasari et al., 2011). According to Madenoğlu et al. (2011), lignin content within biomass feedstock is difficult to gasify, thus less desired in the feedstock.

Most of the reported literature emphasised on the study of operating parameters in gasification process and inorganic element to improve gasification process. Many have analysed the element characteristics of biomass feedstock, such as Son et al. (2011). However, a clear relation between feedstock element characteristic and gasification performance is yet to be established. Thus more work need to be conducted to finalise the key elements that governs gasification technology.

3.2.3 Biomass hydrolysis and fermentation

Biomass hydrolysis is a process to breakdown carbohydrate or cellulosic component within biomass into simple sugar structure. Subsequently, sugar is extracted as product or further processed into downstream chemical product, such as bio-fuel. These are normally catalytic processes with acid or enzyme in temperature and pH sensitive environment.

Several researches have conducted to identify impact of biomass element characteristic to the process yield and efficiency. He et al. (2014) concluded that higher hydrolysis yield of corn stover and higher ethanol yield are due to lower ash content of biomass feedstock. Goh et al., 2010 and Li et al., 2009 proposed that bio-ethanol yield can be estimated based on cellulose and hemicellulose content of the biomass feedstock. Kotarska et al. (2015) suggested that decomposition of lignocellulosic raw material in biomass which consists of cellulose, hemicellulose and lignin increase production yield of ethanol from corn straw in Simultaneous Saccharification and Fermentation (SSF) process. Similarly, Narra et al. (2015) also conducted study of ethanol production from pre-treated lignocellulosic biomass such as rice straw, wheat straw and sugarcane via SSF. Kwietniewska and Tys

(2014) reviewed imperial studies for anaerobic digestion of microalgae biomass in methane fermentation process. The main aspect of the process includes study on substrate composition, process temperature, water content, pH, C/N ratio, organic loading rate, retention time, and inoculums to substrate ratio. Different quality of water is used to assess acid tolerance strain and ethanol production yield from kitchen garbage to decrease process cost (Ma et al., 2009).

No doubt that biomass hydrolysis and fermentation are processes which are sensitive to operating condition such as temperature, pH, and type of enzyme; many have suggested correlation between biomass lignocellulosic elements and the production yield. However, less work is done to analyse the impact of inorganic element towards production yield as well as the interaction between lignocellulosic and inorganic elements.

3.3 Integration platform via biomass element characteristics

Based on the technology review in previous sections, it is clear that most of the technology performances are closely related to biomass feedstock properties. The finding suggested that the main constraint of process input is not subject to biomass species, but it is highly dependent on the feedstock properties. This concept provides a unify approach in biomass feedstock selection, where the selection platform is based on specific element characteristics properties instead of biomass species. Thus, all type of biomass can be considered during the selection stage, including alternative or underutilised biomasses. This integration platform is proposed to be "*Element Targeting Approach*". The platform is expected to have the capability to reflect biomass properties in order to highlight advantages and disadvantages of each biomass species. However, it is also important that the proposed approach is widely used in current research and development to encourage collaboration and expansion work based on existing literatures. This ensure optimum knowledge transfer value chain and minimise extensive research cost and time.

Based on literature review on various biomass process technologies, *proximate analysis* and *ultimate analysis* are generally used to determine chemical and elemental properties of biomass.

Proximate analysis examines moisture content (MC), volatile matter content (VM), fixed carbon content (FC), and ash content (Ash) of biomass: while ultimate analysis determines carbon content (C), hydrogen content (H), nitrogen content (N), oxygen content (O), and sulphur content (S) of biomass. Biomass heating value, either higher heating value (HHV) or lower heating value (LHV) is also one of the commonly analysed properties. These criteria, which are known as biomass element characteristic, are the commonly used approach in current biomass development to identify various biomass properties, either in comparison between different species of biomass or comparison between same species of biomass from different sources. Table 3-1 summarises the fraction of biomass element characteristics data for various biomass species available in literature. From the data compilation, it is demonstrated that identifying biomass element characteristics are common practice in biomass technology research and development. Thus this is able to fulfil the obligations discussed in previous paragraph, where it is very crucial to ensure a common ground to access feedstock properties for all biomass technologies and as a foundation for classification platform to access biomass properties such that all biomass resources can be integrated into the supply chain superstructure. This gives the opportunity to consider all biomass species in the literature within a single platform. Moreover, Table 3-1 acts as a platform to compile biomass properties and element characteristics in order to create a data bank for further reference.

3.4 Methodology of Element Targeting approach

Based on analysis discussed in Chapter 2 and the evaluation of biomass element characteristics in Table 3-1, many researchers have reported the biomass properties based on element characteristic. However, relation between biomass feedstock element characteristics and process technology performance is yet to be fully developed. Nevertheless, a number of researches showed promising relationship in between biomass element characteristics and biomass process technology outputs as discussed in Section 3.2 above. For instance, Mohammed et al. (2011) suggested that biomass with moisture content of more than 50 wt% is not feasible in combustion process. Goh et al. (2010) proposed that the yield of bio-ethanol from biomass can be estimated using

Table 3- 1: Compilation of biomass properties and element characteristics from literature

Biomass	C	H	N	S	O	Ash	FC	VM	MC	LHV	Cell	Hcel	Lig	Reference
Palm Mesocarp Fibre	51.52	5.45	1.89	0.23	40.91	10.83	16.13	73.03	-	19.00	-	-	-	Idris et al., (2012)
	43.19	5.24	1.59	0.19	49.79	10.20	15.20	68.80	-	19.00	-	-	-	Idris et al., (2010)
	50.27	7.07	0.42	0.63	36.28	-	-	-	-	20.64	33.90	26.10	27.70	Kelly-Yong et al., (2007)
	-	-	-	-	-	-	-	-	-	-	34.50	31.80	25.70	Mohammed et al., (2011)
Palm Kernel Shell	48.68	4.77	1.17	0.20	45.27	11.08	15.15	73.77	-	16.30	-	-	-	Idris et al., (2012)
	41.33	4.57	0.99	0.09	53.02	10.5	16.00	69.20	-	16.30	-	-	-	Idris et al., (2010)
	53.78	7.20	0.00	0.51	36.30	-	-	-	-	22.14	20.80	22.70	50.70	Kelly-Yong et al., (2007)
	-	-	-	-	-	-	-	-	-	-	20.80	22.70	50.70	Mohammed et al., (2011)
Empty Fruit Bunch	47.65	5.20	1.82	0.36	44.94	6.10	16.80	77.10	-	16.80	-	-	-	Idris et al., (2012)
	40.93	5.42	1.56	0.31	51.78	15.40	4.50	70.50	-	16.80	-	-	-	Idris et al., (2010)
	48.79	7.33	0.00	0.68	36.30	-	-	-	-	18.96	38.30	35.30	22.10	Kelly-Yong et al., (2007)
	-	-	-	-	-	-	-	-	-	-	38.30	35.30	22.10	Mohammed et al., (2011)

Table 3-1: Compilation of biomass properties and element characteristics from literature (continue)

Biomass	C	H	N	S	O	Ash	FC	VM	MC	LHV	Cell	Hcel	Lig	Reference
	-	-	-	-	-	-	-	-	-	-	38.26	14.62	31.68	Sudiyani et al., (2013)
Palm Kernel Trunk	-	-	-	-	-	-	-	-	-	-	34.50	31.80	25.7	Kelly-Yong et al., (2007)
											37.14	31.80	22.30	Mohammed et al., (2011)
Palm Fronds	-	-	-	-	-	-	-	-	-	-	30.40	40.40	21.70	Kelly-Yong et al., (2007)
	-	-	-	-	-	-	-	-	-	-	49.80	83.50	20.50	Mohammed et al., (2011)
Rubber Wood Chip	46.40	5.70	0.20	0.00	47.70	1.10	10.00	88.90	8.5	17.06	-	-	-	Kaewluan and Pipatmanomai, (2011a)
Shredded Rubber Waste	82.90	8.90	0.30	4.00	3.90	4.80	29.00	66.20	-	-	-	-	-	Kaewluan and Pipatmanomai, (2011b)
Pyrolysis Char of Pine, Tires and Plastic	-	-	-	-	-	0.64 to 2.73	40.00 to 62.50	25.50 to 43.70	-	-	-	-	-	Kelly-Yong et al., (2007)

Table 3-1: Compilation of biomass properties and element characteristics from literature (continue)

Biomass	C	H	N	S	O	Ash	FC	VM	MC	LHV	Cell	Hcel	Lig	Reference
Wood	51.60	6.30	0.00	0.10	41.50	1.00	17.00	82.00	20.00	18.60	-	-	-	McKendry, (2002)
Treated Wood	51.40	6.07	1.24	0.10	41.30	4.90	-	80.30	14.80	-	-	-	-	Vitasari et al., (2011)
Wheat Straw	48.50	5.50	0.30	0.10	3.90	4.00	21.00	59.00	16.00	17.30	33 to 40	20 to 25	15 to 20	McKendry, (2002)
Barley Straw	45.70	5.50	0.40	0.10	38.30	6.00	18.00	46.00	30.00	16.10				McKendry, (2002)
Rice Straw	41.40	5.00	0.70	0.10	39.90	-	-	-	-	-	-	-	-	McKendry, (2002)
Lignite	56.40	4.20	1.60		18.40	6.00	31.00	29.00	34.00	26.80	-	-	-	McKendry, (2002)
Bituminous Coal	73.10	5.50	1.40	1.70	8.70	9.00	45.00	35.00	11.00	34.00	-	-	-	McKendry, (2002)
Miscanthus	48.10	5.40	0.50	<0.10	42.20	2.80	15.90	66.80	11.50	18.50	-	-	-	McKendry, (2002)
Fir	-	-	-	-	-	0.80	17.20	82.00	6.50	21.00	-	-	-	McKendry, (2002)
Danish Pine	-	-	-	-	-	1.60	19.00	71.60	8.00	21.20	-	-	-	McKendry, (2002)
Cereal Straw	-	-	-	-	-	4.30	10.70	79.00	6.00	17.30	-	-	-	McKendry, (2002)
Palm Seed	45.30	5.60	1.00	0.80	47.20	10.80	7.70	76.60	4.90	-	-	-	-	Sait et al., (2012)

Table 3-1: Compilation of biomass properties and element characteristics from literature (continue)

Biomass	C	H	N	S	O	Ash	FC	VM	MC	LHV	Cell	Hcel	Lig	Reference
Palm Leaf	49.30	5.80	1.20	1.30	42.30	11.70	5.20	78.10	5.00	-	-	-	-	Sait et al., (2012)
Palm Leaf Stem	36.10	5.20	0.70	0.70	57.20	19.20	7.80	55.30	17.70	-	-	-	-	Sait et al., (2012)
Municipal Solid Waste	55.20	1.72	1.95	1.40	38.53	44.20	-	-	38.50	10.45				Vitasari et al., (2011)
Sludge	50.20	7.15	5.26	1.76	35.30	35.10	-	88.20	32.10	-				Vitasari et al., (2011)
Cauliflower Residue	40.20	5.40	3.10	0.50	45.85	15.00	-	-	12.00	-	31.10	5.40	3.90	Madenoğlu et al., (2011)
Acorn	48.50	5.30	0.40	0.80	43.46	2.50	-	-	12.90	24.80	16.50	12.50	45.10	Madenoğlu et al., (2011)
Tomato Residue	54.70	7.60	2.90	0.60	31.68	3.70	-	-	7.50	-	24.00	17.00	21.90	Madenoğlu et al., (2011)
Extracted Acorn	48.60	5.80	0.70	0.90	43.11	4.30	-	-	10.80	-	38.70	15.10	23.50	Madenoğlu et al., (2011)
Hazelnut Shell	52.20	5.90	0.45	0.60	39.71	1.70	-	-	6.80	-	38.20	12.10	40.00	Madenoğlu et al., (2011)
Corn Cob	43.24	5.28	0.44	0.08	41.02	2.90	17.39	72.67	7.04	-	-	-	-	Lu et al., (2012)

Table 3-1: Compilation of biomass properties and element characteristics from literature (continue)

Biomass	C	H	N	S	O	Ash	FC	VM	MC	LHV	Cell	Hcel	Lig	Reference
Corn Cob Briquette	-	-	-	-	-	4.35	79.37	15.63	0.64	-	-	-	-	Nuriana et al., (2014)
Gasification Particle	88.20	0.53	0.57	0.09	4.11	8.10	84.40	6.50	1.00	29.80	-	-	-	Miguel et al., (2012)
Durian Peel Briquette	-	-	-	-	-	18.18	77.87	3.94	0.01	26.29	-	-	-	Nuriana et al., (2014)
Jarak Wood Briqutte	-	-	-	-	-	11.80	66.01	20.90	5.87	21.99	-	-	-	Nuriana et al., (2014)
Cocoa Peel Briqutte	-	-	-	-	-	18.98	49.93	24.99	10.67	18.32	-	-	-	Nuriana et al., (2014)
Durian Shell	60.31	8.47	3.06	0.10	28.06	2.52	22.36	69.59	5.53	-	-	-	-	Chandra et al., (2009)
	39.30	5.90	1.00	0.06	53.74	4.84	-	-	11.27	-	73.54	13.09	15.45	Jun et al., (2010)
Durian Peel	42.86	5.71	0.18	51.25		4.22	21.42	69.82	4.54	-	-	-	-	Foo and Hameed, (2011) and Nuithitikul et al., (2010)

the feedstock's cellulose content. These research outcomes further solidify the concept of biomass element characteristics as the integration platform for biomass feedstock selection as shown in previous Figure 3-2. Thus, element targeting approach is introduced to integrate multiple biomass resources into existing biomass supply chain network for optimum biomass utilisation. Element targeting utilises biomass element characteristic as a platform to evaluate the implementation feasibility of respective biomass species in a particular biomass process technology as shown in Figure 3-3.

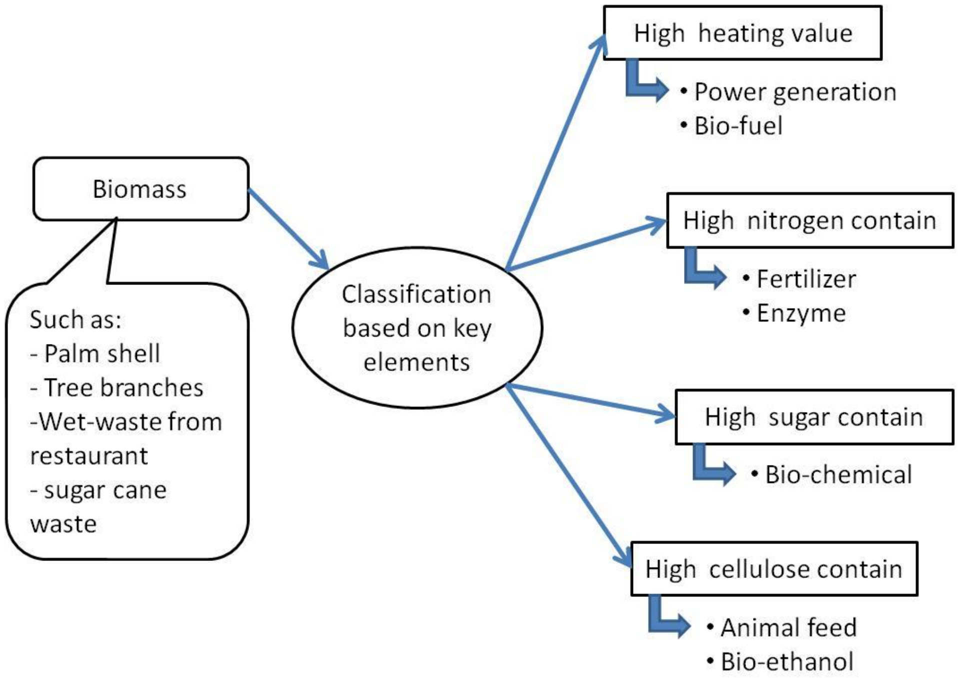


Figure 3- 3: Element targeting illustration

Nevertheless, there are challenges to integrate biomass feedstock via element characteristics due to limited knowledge and research on the impact of different biomass elemental properties to process performance (such as production yield and product quality). It is very important that the proposed element targeting approach is based on *key elements* that contribute significantly to process performances. Key elements are not only limited to elemental and chemical characteristics from proximate and ultimate analysis. Other critical feedstock properties for respective process technology are also required to be considered. For example, biomass feedstock size, mineral content, and cellulosic content (such as cellulose, hemicellulose and lignin) as suggested by Goh et al. (2010) for bio-ethanol production. Therefore, the key elements of a respective biomass process technology are highly dependent on the element acceptance range for the selected technology.

Element acceptance range is a set of boundaries of key elements such that any biomass feedstock falls within this range will not have significant impact to the process performance. This concept is based on the fundamental theory of mass balance in chemical engineering, where all input of process should be same as the output. In other words, if all the key elements of the process feedstock are addressed according to the element acceptance range (disregard any biomass species or mixture of biomasses), the respective technologies are expected to give similar process performance without major process modification. Two approaches are introduced in this research to construct element acceptance range for biomass process technology. The principle of these approaches is discussed in detail below.

3.4.1 Element acceptance range based on literature and technology expertise

Element targeting approach is proposed to integrate multiple biomass species into existing technology via element characteristics. However, due to lack of research on the impact of each element characteristics to the process output and performance, construction of element acceptance range of each technology is required. One of the straight forward approaches to determine technology element acceptance range is based on literature data or industrial input. This method harvests the data and knowledge on the key elements of respective technology and their impact to the technology outputs. In other words, the key element of the technology is already pre-defined by expertises. For example, Goh et al. (2010) and Li et al. (2009) reported that bio-ethanol yield can be estimated based on feedstock cellulose and hemicellulose content. Mohammed et al. (2011) stated that biomass combustion generally has energy efficiency in the range of 10% to 30% provided that the moisture content of biomass feedstock is less than 50 wt%. Both literatures do not indicate any upper limit for the technology tolerances to feedstock element characteristics. Thus, it is assumed that both technologies are able to accept any type of feedstock. Figures 3-4 and Figure 3-5 show the element acceptance range for respective technologies. By utilising this information, selection of alternative biomass as feedstock is possible to enhance integration of various biomass species into the system. However, noted that this approach may underestimate the key elements of the technology. The element acceptance range constructed in Figures 3-4 and 3-5 has huge tolerance to accept any type of biomass properties due to the lack of constraint input from literature. This may results in inconsistency of technology performance when translate to real life application. Hence, more studies need to be conducted to ensure all key elements of the technology are addressed. Nevertheless, this approach to construct element acceptance range is feasible provided that the technology has a clear definition of key elements and their impact to technology performance.

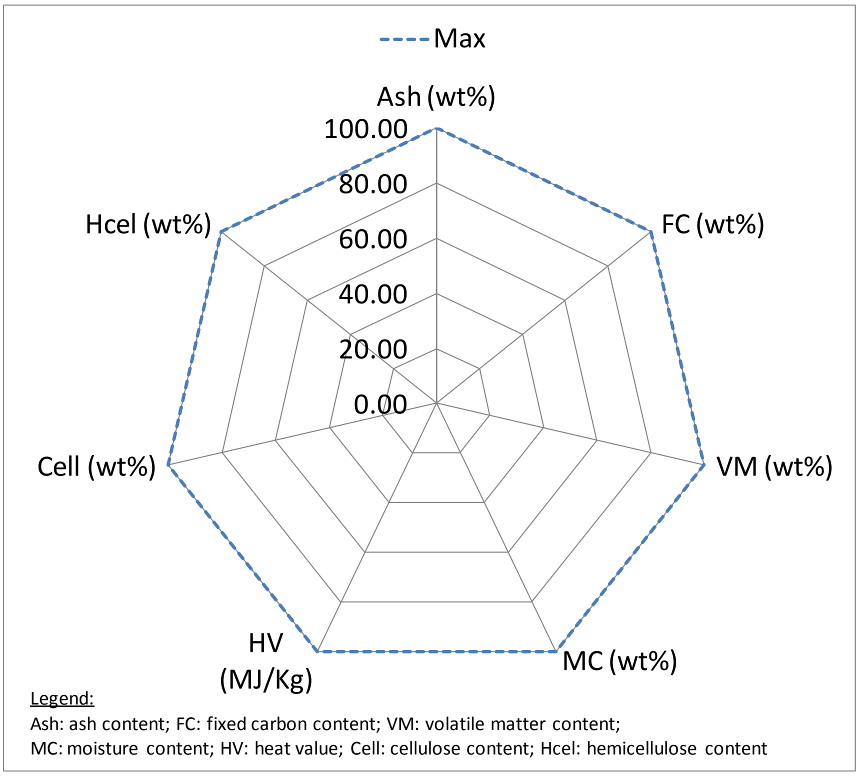


Figure 3- 4: Element acceptance range for bio-ethanol fermentation technology

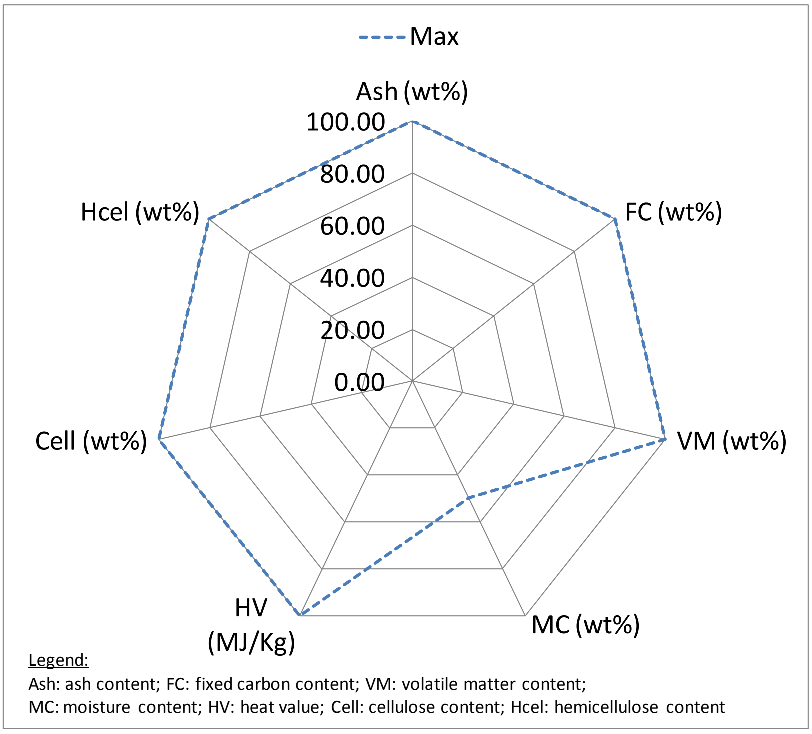
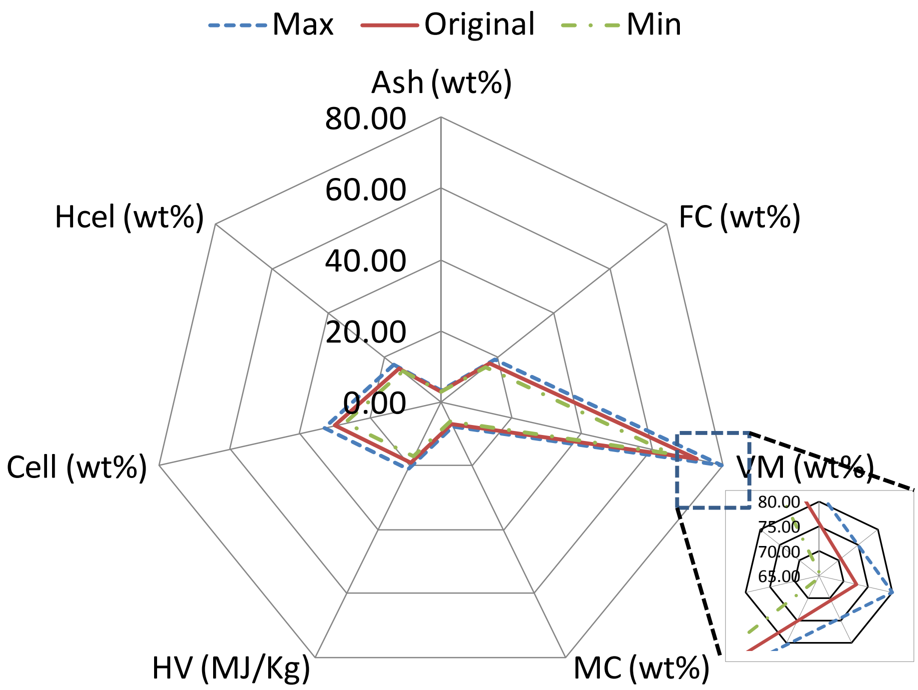


Figure 3- 5: Element acceptance range for combustion technology

3.4.2 Element acceptance range based on element deviation factor (f_e)

On the hand, due to the lack of study on the impact of biomass feedstock element characteristics to process technology performance, it is very difficult to construct element acceptance range for many biomass process technologies. Study on the relation between feedstock element characteristics and process performance for each technology required much time and cost. This will further constraint the implementation of the technology and restricts integration of underutilised biomass into the existing system. In order to deal with this problem, a second approach to construct element acceptance range is introduced to promote element targeting approach. This approach utilised the original biomass properties as the guideline for the construction of element acceptance range. Since the key elements are yet to be identified, all element characteristics are assumed to be equally important, hence all elements are considered to be the key elements. An element deviation factor is introduced to reflect the fluctuation of original biomass feedstock properties. These fluctuations create an upper and lower boundary for the biomass feedstock element characteristics to capture the deviation of biomass properties. Generally biomass properties deviate due to several factors such as origin of biomass collected, weather and storage period. Fournel et al. (2015) discussed the biomass properties (MC, LHV, bulk density, C, H, N, O, Ash, and minerals) fluctuation according to seasonal changes. Generally the fluctuation is in the range of 0 % to about 20 % of the average values, while mineral content can fluctuate up to 90 % (in term of quantity is actually relatively small as the mineral content is measure in milligrams). Shabani and Sowlati (2016) also stated that the biomass obtained for a power plant has the fluctuation of MC and HV in the range of ±16.7 % and ±5.9 % respectively. This creates degree of freedom for the technology to select alternative biomass species as feedstock, as long as the overall feedstock properties are within the boundary.

For example, Lu et al. (2012) reported that the hydrogen yield in supercritical water gasification is 30.46 g/kg feedstock by using corn cob as the feedstock. Based on the original corn cob element characteristics, the element acceptance range for the technology is constructed with an element deviation factor of ±10 % as shown in Figure 3-6. Note that ±10 % is a very conservative assumption based on the general biomass fluctuation as discussed above to ensure minimum changes in process performance. Due to the relatively small range between the upper and lower boundary, a small section of the chart is enlarged for visual clarification. The technology element acceptance range is calculated via Equation 3-2 and Equation 3-3, where *E_Upper(e,j)* and *E_lower(e,j)* is upper and lower boundary of element acceptance range at each process plant respectively, and *E_ori(e,j)* is the element characteristics of the original biomass feedstock used in respective process plant. However, the proposed element acceptance range is only feasible provided that the operating conditions and equipment set up are remained unchanged. The main advantage of this approach is to allow construction of element acceptance range for technology where the relation between key elements and their impact to its technology performance is yet to be developed. By assuming that all element characteristic are equally important, element targeting approach can be implemented into various technologies as long as the element characteristics of the original biomass feedstock is provided.



Legend:
Ash: ash content; FC: fixed carbon content; VM: volatile matter content;
MC: moisture content; HV: heat value; Cell: cellulose content; Hcel: hemicellulose content

Figure 3- 6: Element acceptance range for hydrogen production by supercritical water gasification technology

$$E\_upper(e,j) = E\_ori(e,j) + [E\_ori(e,j) \times f_e] \tag{3-2}$$

$$E\_lower(e,j) = E\_ori(e,j) - [E\_ori(e,j) \times f_e] \tag{3-3}$$

3.5 Demonstration of element targeting approach

Based on the discussion in Section 3.3, biomass properties are proposed to be classified based on element characteristics; while discussion in Section 3.4 suggested that each technology has their tolerances to accept a certain property range of biomass element characteristics, which is known as element acceptance range. In this section, a simple demonstration of element targeting approach is constructed to show the integration and selection of multiple biomass feedstock based on technology element acceptance range.

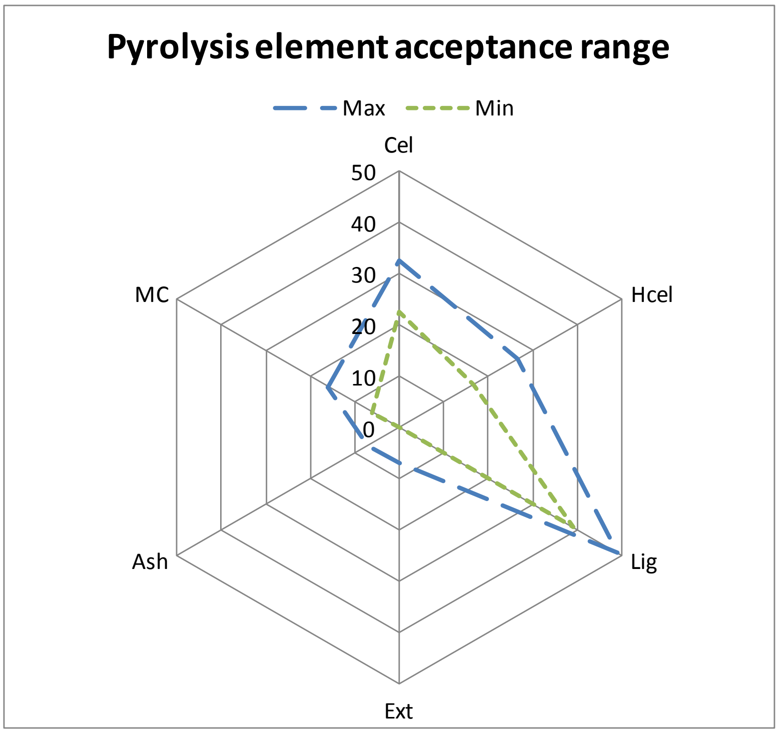
In order to simplify the example, only two types of biomasses (rubber wood chip and wheat straw), two element characteristics (moisture content and heat value), and an existing process technology (combustion) are considered. Table 3-2 summarised the element characteristics of the biomasses. For demonstration purpose, assuming the existing combustion technology is designed only based on rubber wood chip as feedstock, and alternative biomass species has yet to be tested in this technology set up. Thus, wheat straw is not being considered in the system, hence is classified as underutilised biomass. In the case of system fluctuation, such as increase of production or decrease of rubber wood chip availability, the process system has to import additional rubber wood chip from other regional area to fulfil the technology feed requirement. Alternative, a new process technology can be introduced to utilise wheat straw to convert into valuable downstream product.

Table 3- 2: Biomass properties

Biomass	Moisture content (MC), wt%	Heat value (HV), MJ/kg	Reference
Rubber Wood Chip	8.5	17.06	Kaewluan and Pipatmanomai, (2011a)
Wheat Straw	16.00	17.30	McKendry, (2002)

Based on the proposed element targeting approach, the biomass feedstock selection criteria is suggested to be based on biomass element characteristics instead of biomass species. Assuming in this case study, the maximum tolerance of MC is 10 wt% and the feedstock HV is required to be 1000 MJ. In normal operation, total of 58.6 kg of rubber wood chip (with MC of 8.5 wt%) is required and wheat straw alone is not suitable for the process due to high MC. However, in special case where availability of rubber wood chip within the local region is less than the requirement, the conventional feedstock integration approach will suggest importation of rubber wood chip from other region due to the selection criteria is based on biomass species (provided that the solution is economically viable). Alternative solution is to introduce a pretreatment unit to remove MC of wheat straw, such that it can be used as supporting feedstock. Conversely, implementation of element targeting approach enable the system to decide the optimum biomass feedstock based on element characteristics. Thus, an alternative solution is to combine both rubber wood chip and wheat straw to achieve the required 1000 MJ feedstock, as long as the combined MC is less than 10 wt%, which the maximum tolerance for wheat straw is approximately 11.7 kg, with approximately 46.8 kg of rubber wood chip. This solution has the potential to reduce the possibility of increasing logistic cost due to importation and capital cost due to investing in new technology. In addition, underutilised biomass such as wheat straw (in this case) is considered in the process to convert into higher value product. With consideration of underutilised biomass, this approach enable optimisation of process to maximise profit (underutilised biomasses are generally available at lower cost due to low demand) or maximise biomass utilisation (enhance possibility of application of underutilised biomasses).

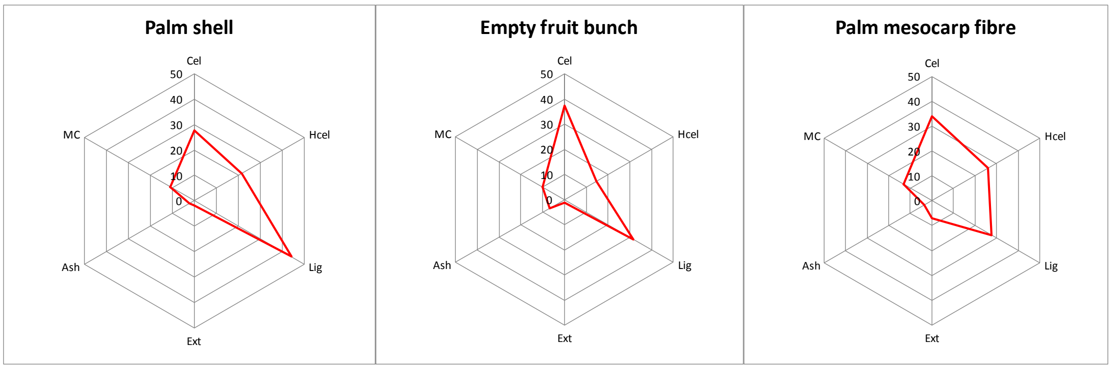
However, the problem will be more complex in real life scenario which involved more variables, such as more biomass element characteristics. For example, Figure 3-7 presented the element acceptance range for a pyrolysis technology based on palm shell as original feedstock.



Legend:
Cell: cellulose content; Hcel: hemicellulose content; Lig: lignin content
Ext: extractive content; Ash: ash content; MC: moisture content

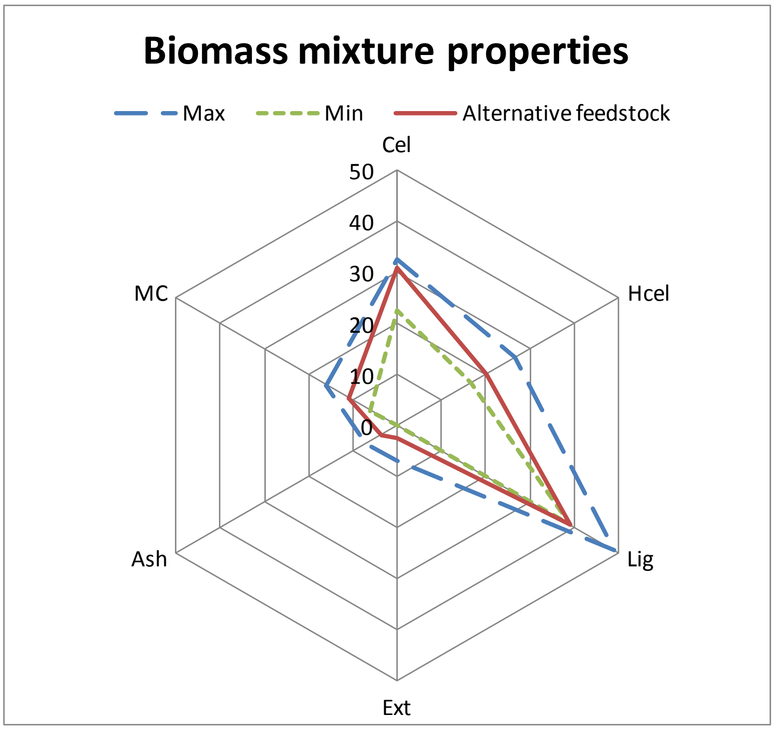
Figure 3- 7: Example of element acceptance range of palm shell pyrolysis technology

Figure 3-8 presented three biomass species available in the system, namely palm shell, empty fruit bunch, and palm mesocarp fibre. Based on the same concept of element targeting in previous simplified example, these three biomasses are mixed as alternative feedstock to replace 100 wt% of original feedstock. The proposed biomass mixture element characteristics must be within the element acceptance range of the technology. Figure 3-9 demonstrated the predicted mixture element characteristics (63 wt% palm shell; 26 wt% empty fruit bunch; 11 wt% palm mesocarp fibre) and is superimposed into Figure 3-7. The properties of biomass mixture is predicted based on linear relation and mass fraction of pure biomass as shown in Equation 3-4 below.



Legend:
Cell: cellulose content; Hcel: hemicellulose content; Lig: lignin content; Ext: extractive content; Ash: ash content; MC: moisture content

Figure 3- 8: Radar chart for biomass element characteristics



Legend:
Cell: cellulose content; Hcel: hemicellulose content; Lig: lignin content
Ext: extractive content; Ash: ash content; MC: moisture content

Figure 3- 9: Biomass mixture element characteristics superimposed into element acceptance range

$$Biomass\ mixture\ properties \\ = (Biomass\ "1"\ fraction \times Bomass\ "1"\ properties) \\ + (Biomass\ "2"\ fraction \times Biomass\ "2"\ properties) + \\ \ldots + (Biomass\ \text{"n" fraction} \times \text{Biomass "n" properties}) \tag{3-4}$$

The methodology of biomass mixture properties prediction in Equation 3-4 is similar to the properties integration approach in process integration to determine mixed stream properties. Generally properties integration of process stream can be categorised into mass conserved and non-mass conserved properties. Mass conserved properties refer to the properties that follow concept of mass balance, where the mixed properties estimation is based on mass/component fraction, such as composition and temperature. On the other hand, some properties such as density, viscosity, thermal conductivity, pH value, and toxicity are not conversed, thus do not follow the linear relation with respect to mass ratio (Sandate-Trejo et al., 2014). In order to have accurate properties prediction, many studies have conducted to determine the correlation and prediction models for mixture properties (González et al., 2007). Tables 3-3(a) and 3-3(b) summarised some of the examples of properties operators and integration models reported in literatures.

Table 3-3(a): Generic property operator summarised by Jiménez-Gutiérrez et al., (2014)

Property	Operator
Composition	$\psi_m(\text{Composition}) = \text{Composition}$
Toxicity	$\psi_m(\text{Toxicity}) = \text{Toxicity}$
Chemical oxygen demand	$\psi_m(\text{Chemical oxygen demand}) = \text{Chemical oxygen demand}$
pH	$\psi_m(\text{pH}) = 10^{\text{pH}}$
Density, ρ	$\psi_m(\rho) = \frac{1}{\rho}$
Viscosity	$\psi_m(\text{Viscosity}) = \log(\text{Viscosity})$
Vapour pressure	$\psi_m(\text{Vapour pressure}) = \text{Vapour pressure}^{1.44}$
Electric resistivity	$\psi_m(\text{Electric resistivity}) = \frac{1}{\text{Electric resistivity}}$
Reflectivity	$\psi_m(\text{Reflectivity}) = \text{Reflectivity}_m^{5.92}$
Colour	$\psi_m(\text{Colour}) = \text{Colour}^{0.606}$
Odour	$\psi_m(\text{Odour}) = \text{Odour}$

Table 3-3(b): Property integration models

Property	Integration model	Reference
Sulphur content, S	$$S_{mixture} = \sum_{m=1}^{M} x_m S_m$$	Shelley and El-Halwagi (2000)
Liquid density, ρ	$$\frac{1}{\rho_{mixture}} = \sum_{m=1}^{M} \frac{x_m}{\rho_m}$$	
Reid vapour pressure, RVP	$$RVP_{mixture}^{1.44} = \sum_{m=1}^{M} x_m RVP_m^{1.44}$$	
Kinematic viscosity, ν	$$\ln(\nu_{mixture}) = \sum_{m=1}^{M} x_m \ln(\mu_m) \sum_{m=1}^{M} \frac{x_m}{\rho_m} + \frac{\Delta * G^E}{RT}$$	Sandate-Trejo et al., (2014)
Thermal conductivity, λ	$$\log(\lambda_{mixture}) = \sum_{m=1}^{M} x_m \log(\lambda_m) + A_1 + A_2\dot{T}$$	
Kinematic viscosity, ν	$$\ln(\nu_{mixture} M) = \sum_{m=1}^{M} x_m \ln(\nu_m M_m) + \frac{\Delta * G^E}{RT}$$	González et al., (2007)

x: mole fraction; $\Delta * G^E$: Gibbs free energy; μ: dynamic viscosity; A_1 and A_2: empirical parameters estimated via minimum square techniques; $\dot{T}$: temperature function; M: molar mass

Based on Table 3-3(b), estimation of sulphur content in a mixture is proposed to be in a linear relation with respect to the mass faction and the sulphur content of the individual material. This is due to sulphur content is a mass-conversed property that based on the component or mass fraction of the material. On the other hand, density of a liquid mixture is unable to be predicted based on linear mass or component fraction of individual material, but instead based on the correlation proposed in both Tables 3-3(a) and 3-3(b). Similar to sulphur content, RVP is suggested to be a mass-conversed property. This is supported by Roult's law which stated that liquid vapour pressure of a mixture is correlated to the mole fraction and vapour pressure of individual liquid. Although both integration models for kinematic viscosity and thermal conductivity are correlated to mole fraction, however, the models do not obey the linear relation with respect to mole, mass or component fraction. Nonetheless, both kinematic viscosity integration models proposed by Sandate-Trejo et al., (2014) and González et al., (2007) are theoretically the same, where the only difference is Sandate-Trejo et al., (2014) expressed the molar mass, M in terms of dynamic viscosity, μ, mass/mole fraction, x, and density, ρ. Both of the proposed models for kinematic viscosity has considered the non-ideal case scenario as compared to the ideal case scenario (generic) operator proposed in Table 3-3(a) for mixture viscosity estimation.

Discussions above have shown that researchers had proposed various properties integration models to predict different properties. However, most of the studies are focused on the properties integration of process fluid and less literature reported on the solid property integration model. Nonetheless, the biomass (solid) properties to be considered in this thesis, namely C, H, N, O, S, MC, FC, Ash, VM, HV, Cell, Hcel, and Lig, are presumed to be correlated to the material mass fraction. Thus, the prediction model is proposed to be in a linear relation with respect to the mixing ratio as per Equation 3-4. This prediction model will be verified in Chapter 5 via laboratory analysis.

To summarise, there are two main assumptions to be verified in the proposed element targeting approach. First, as discussed above, the element characteristics of the biomass mixture are assumed to be correlated to mass fraction and able to predict based on the pure biomass element characteristics in a linear relation. Second assumption is, as discussed in Section 3.4.1 and Section 3.4.2, no major process performance fluctuation is expected if the feedstock element characteristics are within the element acceptance range of the technology. Both of the assumptions will be verified in Chapter 5 to ensure applicability into biomass supply chain optimisation model.

3.6 Conclusions

A systematic biomass classification approach is introduced in this chapter to act as a platform to consider underutilised/alternative biomasses as potential resources for existing biomass technologies. Element characteristics are suggested to use as the selection criteria to integrate underutilised biomass into existing system as it is a commonly used methodology to define biomass properties. Nevertheless, in order to integrate alternative biomass into existing process technology, element acceptance range is introduced to set the upper and lower boundaries of the technology tolerances toward feedstock fluctuations, and ensure consistency of the technology performance. Two approaches were suggested to construct element acceptance range. However, more studies are required to enhance the system by considering more biomass species and technologies into the system.

Chapter 4:
ELEMENT TARGETING APPROACH FOR BIOMASS GASIFICATION TECHNOLOGY

In previous chapter, a novel concept of element targeting approach was proposed to integrate alternative or underutilised biomass into the existing biomass process technologies. The fundamental idea is to determine the feasibility of implementing alternative biomass into existing process based on the element acceptance range of respective process technology. Each process technology is suggested to have a unique element acceptance range, such that any biomass feedstock with element characteristics within the range will not have major impact to the process performance. This integration approach introduced biomass feedstock selection based on element characteristics instead of biomass species which provides higher flexibility in supply chain management compared to the conventional biomass supply chain optimisation approaches. However, before implementing the new approach into biomass supply chain optimisation model, it is important to ensure the applicability of the element targeting approach in real life scenario. In this chapter, concept of element targeting approach is verified via existing literature. Biomass gasification technologies are used in the case study due to the popularity in biomass development. The main advantage to initiate prove of concept via literature is to have a preliminary verification before venturing into larger investment, the laboratory experiment. In addition, it also enables verification of applicability of the new concept into existing technologies.

4.1 Biomass Gasification and its Current Limitations

As the efforts to explore alternative resource for more sustainable and renewable energy system, biomass has becomes one of the promising substitution for conventional fossil fuel. High availability, enhance development of rural area, zero carbon dioxide balance and multiple adaptation in varies technologies gave biomass more advantages with respect to other renewable resources

(Á.Murillo et al., 2015). Among the biomass technologies, gasification is one of the well established technologies in terms of conversion to energy and hydrogen production.

However, implementation of gasification plant is yet to be perfected due to several drawbacks. For example, low energy efficiency and high operating cost are the few of the critical issues to be rectify. Research and development of biomass gasification has also ventured into catalytic reaction to enhance overall gasification performance. Many catalysts are studied to increase the production yield, for instance dolomite, olivine and alumina are well-known catalysts in biomass gasification for tar removal Andrés et al., (2011). The study concluded that dolomite has the highest efficiency to remove tar and increases hydrogen gas yield.

General biomass supply chain is also part of the problem to implement biomass gasification plant as discussed in Chapter 2. Relatively low density of biomass resulted in high transportation cost (Pirraglia et al., 2013). Moreover, availability of each biomass species is subjected to the regional biomass system, thus not all areas have sufficient mainstream biomass for mass production. The current state of research and development on biomass gasification technology is lacking on investigation of integrating various alternative biomass species into the existing technology as discussed in Section 3.2.2. Many biomass gasification researches were conducted based on specific biomass species, where the impact of integrating alternative biomass species to the technology performance is unknown. This creates another huge gap in implementing biomass gasification technologies, where different biomass species as feedstock leads to different technology output and performance. Thus, it is essential to implement element targeting approach in biomass gasification technologies to enhance multiple biomass integration into existing technologies. In order to implement element targeting approach into biomass gasification technologies, the element acceptance range of the technology needs to be constructed first.

4.2 Objectives

The main target of this chapter is to investigate the relation of biomass feedstock element characteristics with respect to the biomass gasification output performance and to construct the element acceptance range for biomass gasification technologies. Several biomass gasification technologies are compiled and used as case study to verify the concept. The differences in gasification process output such as the energy and yield due to different feedstock element characteristics are compared, in order to construct the element acceptance range for the technology. This case study will focus on the impact of feedstock element characteristics to the produced syngas heating value (HV) via biomass gasification technologies. Analysing syngas HV as the main process output helps to determine the feasibility of implementing biomass gasification power plant for energy generation with multiple biomass species as feedstock.

4.3 Review of Syngas Production via Biomass Gasification Technologies from Literatures

Many researches have been conducted to improve biomass gasification in term of higher efficiency and lower operating cost. In order to construct the element acceptance range for biomass gasification technologies, information on biomass feedstock element characteristics are required. Subsequent paragraphs evaluated several literatures on biomass gasification technologies with the information regarding biomass feedstock element characteristics. Being one of the main conversion processes to convert biomass into biofuel such as syngas and hydrocarbons, heating value (HV) is one of the main product properties to determine the fuel quality. Thus, this study will focus on the impact of syngas HV and only the literatures with information regarding syngas HV are selected for this case study. This information is used as the input data to construct element acceptance range for biomass gasification technologies.

Dudyński et al., (2015) investigated the influence of torrefaction on syngas production and tar formation in biomass gasification on an industrial-scale gasifier. Four different biomass species were used in the study including, polish pellet (60 % pine and 40 % hardwood), torrefied pellet, South

Africa pellet (100% pine) and polish sawdust. Á.Murillo et al., (2015) analysed the impact of carbon densification via hydrocarbonization of biomass with respect to steam gasification process. The work covered multiple sets of experiment alternating gasification temperature, steam flowrate and biomass feedstock species. González et al., (2011) studied cracking of tars by dolomite in two-stage olive cake gasification. The results difference due to different operating temperature are analysed and compared with non-catalyst process. Biomass gasification in a fluidized bed reactor was investigated by Barisano et al., (2015) to achieve optimum operating condition. Kihedu et al., (2015) explored the performance of air-steam auto thermal updraft gasification of biomass with respect to the air gasification in packed bed reactor. Air-steam gasification is reported to have higher syngas low heating value, tar generation, cold gas efficiency, and carbon conversion. Similarly, Roche et al., (2014) investigated air and air-steam gasification of biomass, in this case, sewage sludge and the impact of dolomite as catalyst with respect to tar production and composition. The result is comparable with Kihedu et al., (2015) as the present of steam as gasifying agent enhance overall syngas production. Moghadam et al., (2014) looked into the effect of temperature, catalyst, equivalence ratio and steam/biomass ratio in a coconut shell biomass conversion process integrated with pyrolysis and air-steam gasification process. The optimum operating condition is reported to be 500 °C and 950 °C for pyrolysis and gasification respectively with equivalence ratio from 0.23 to 0.24 and steam/biomass ratio ranged from 1.9 to 2.5. Tursun et al., (2015) investigated steam co-gasification of pine sawdust and bituminous coal in a lab-scale external circulating radial-flow moving bed gasification system. Calcined olivine was used as catalyst for tar cracking and as circulating heat carrier. Multiple biomass blending ratio between pine sawdust and bituminous coal are attempted to investigate the impact to the reactor output.

Based on the gasification technologies above, the relationship between biomass feedstock element characteristics and the process output is investigated. Table 4-1 summaries the syngas HV produced from each technology with respect to their biomass feedstock and operating condition. Each works from literature is considered as unique technology that differs from each other due to the different equipment setup, sizes, and operating conditions.

Table 4- 1: Summary of gasification technologies based on literatures

Literature Source	Biomass	Gasification Temperature (°C)	Gasification pressure	Syngas Heating Value (HV) (MJ/Nm^3)	Oxidation agent	Catalyst
Dudyński et al., (2015)	Polish pellet (60% pine and 40% hardwood)	550	atm	5.65	Air flow rate at 100 m^3/h	-
	Torrefied pellets			6.11	Air flow rate at 40 m^3/h	
	South Africa pellet (100% pine)			5.00	Air flow rate at 90 m^3/h	
	Polish sawdust			3.06	Air flow rate at 35 m^3/h	
Á.Murillo et al., (2015)	Pristine olive waste	700	atm	6.56	(steam flowrate at 1 g/min)	-
	Char			6.48		
	Hydrochar			8.29		
	Pristine olive waste	900		8.34	(steam flowrate at 1 g/min)	-
	Char			7.55		
	Hydrochar			10.22		
	Pristine olive waste	900		7.10	(steam flowrate at 0.5 g/min)	-
	Char			8.99		
	Hydrochar			9.04		
González et al., (2011)	Olive cake	800	atm	11.35	110 mg/min	dolomite
				11.88		
		900		10.67	110 mg/min	dolomite
				9.73		
		1000		11.21	190 mg/min	-

Table 4-1: Summary of gasification technologies based on literatures (continue)

Literature Source	Biomass	Gasification Temperature (°C)	Gasification pressure	Syngas Heating Value (HV) (MJ/Nm^3)	Oxidation agent	Catalyst
				9.57	110 mg/min	-
Kihedu et al., (2015)	Black pine pellet	943	atm	4.45	Air-steam at 2.85 equivalence ratio	-
Roche et al., (2014)	Dry sewage sludge	800	atm	3.10	Steam-to-biomass ratio of 1	dolomite
Barisano et al., (2015)	Almond shell	825	atm	11.35	Steam-to-biomass ratio of 0.4 O_2-to-biomass ratio at 0.3	-
Moghadam et al., (2015)	Coconut shell	950	Atm	12.54	Air-to-biomass equivalence ratio at 0.23 Steam-to-biomass ratio at 2.45	dolomite
Tursun et al., (2014)	Pine sawdust	800	atm	6.90	Steam/carbon ratio of 1.3	-
	25 wt% pine sawdust and 75 wt% bituminous coal			9.00		
	50 wt% pine sawdust and 50 wt% bituminous coal			10.95		
	75 wt% pine sawdust and 25 wt% bituminous coal			11.48		
	Bituminous coal			11.79		

Table 4-2 listed the element characteristic of each biomass as reported in their respective literature. Two different units of HV are found to be used in these literatures, lower heating value and higher heating value. This creates inconsistency in the analysis. However, the differences are considered to be within an acceptable range as generally the difference between lower heating value and higher heating value are within 10 %. On the other hand, element characteristic for dry sewage waste is incomplete as per the literature. Roche et al., (2014) reported the overall organic matter within dry sewage waste as 58.3 wt%, instead of analysing the volatile matter and fixed carbon content. In addition, some of the literatures did not report the heating value of the biomass feedstock as part of the element characteristic. This issue is rectified by using correlation in Equation 4-1, which was suggested by Nhuchhen and Salam (2012) to estimate the biomass HV. This prediction model is based on 250 species of biomasses ranged from fruit waste (such as almond shell, hazelnut shell, and coconut shell), agriculture waste (such as rice husk, corn cob, and wheat straw), wood chips (such as bamboo, pine wood, and softwood), grasses (such as sugar cane leaves, switch grass and tea bush), and pellets (such as charcoal, pine pellet, and miscanthus pellet). The results have shown that the proposed non-linear correlation has less estimation errors as compared to other researches.

$$HV = 20.7999 - 0.3214 \times \frac{VM}{FC} + 0.0051 \times \left(\frac{VM}{FC}\right)^2 - 11.2277 \times \frac{Ash}{VM} + 4.4953\left(\frac{Ash}{VM}\right)^2 - 0.7223 \times \left(\frac{Ash}{VM}\right)^3 + 0.0383 \times \left(\frac{Ash}{VM}\right)^4 + 0.0076 \times \frac{FC}{Ash} \quad (4\text{-}1)$$

4.4 Analysis of general relation between feedstock element characteristics and syngas heat value in biomass gasification

The first attempt in this work is to evaluate the relation of feedstock element characteristics with the produced syngas HV. In this case, information on various different gasification technologies are complied and analysed. Based on the information tabulated in Table 4-1, different feedstock and operating conditions will generate different process output (syngas HV). Based on data of biomass element characteristics in Table 4-2, 10 graphs of each element characteristics of feedstock versus syngas HV are plotted as shown in Figure 4-1. Relation of biomass feedstock with respect to gasification output is then analysed by comparing the impact of feedstock element characteristic to

Table 4- 2: Biomass element characteristics based on literatures

Literature Source	Biomass	C (wt%)	H (wt%)	O (wt%)	N (wt%)	S (wt%)	MC (wt%)	VM (wt%)	FC (wt%)	Ash (wt%)	HV (MJ/kg)
Dudyński et al., (2015)	Polish pellet (60% pine and 40% hardwood)	52.6	5.9	41.3	0.3	0.0	10.0	70.0	19.5	0.5	19.9*
	Torrefied pellets	56.0	5.0	38.6	0.4	0.0	4.5	60.0	34.5	1.0	20.3*
	South Africa pellet (100% pine)	53.4	5.5	40.7	0.4	0.0	10.0	78.4	16.4	5.0	18.7*
	Polish sawdust	51.8	5.7	42.2	0.1	0.2	50.0	41.9	7.4	0.7	19.0*
Á.Murillo et al., (2015)	Pristine olive waste	45.6	6.2	47.9	0.3	0.0	10.4	71.8	16.4	1.4	16.9
	Char	86.8	2.1	10.8	0.3	0.0	2.1	24.3	71.5	2.1	32.6
	Hydrochar	66.2	5.1	28.5	0.2	0.0	3.7	53.9	40.4	3.7	26.6
González et al., (2011)	Olive cake	48.7	6.3	44.3	0.6	0.1	0.0	72.3	23.1	4.6	19.2*
Barisano et al., (2015)	Almond shell	47.9	6.3	44.3	0.3	0.0	0.0	80.6	18.2	1.2	19.5*
Kihedu et al., (2015)	Black pine pellet	49.3	6.7	43.2	0.9	0.0	4.6	83.6	15.8	0.6	19.4*
Roche et al., (2014)	Dry sewage sludge	29.5	4.9	15.0	4.1	1.6	8.7	-	-	41.7	-
Moghadam et al., (2015)	Coconut shell	50.2	5.4	43.4	0.9	0.1	8.6	52.6	26.5	12.4	21.5
Tursun et al., (2014)	Pine sawdust	47.8	6.9	44.8	0.1	0.4	8.3	78.4	12.7	0.6	19.1
	bituminous coal	77.0	4.1	17.6	0.7	0.6	10.5	28.9	57.0	3.7	28.0

*calculated using correlation suggested by Nhuchhen and Salam (2012) produced syngas HV. In order to evaluate the general relation in gasification technology, this analysis is conduced disregard of the differences in operating conditions and equipment set up. However, no obvious trend is observed as shown in Figure 4-1. All the data are scattered around and is very difficult to conclude a relation. Thus, the analysis concluded that it is very complex to construct a systematic relation between the biomass feed and process output with different technologies. This is due to inconsistency of variables in terms of gasification temperature, oxidation agent, catalytic and non-catalytic process, steam flowrate, steam/biomass ratio, and operating conditions.

Nevertheless, it is observed that some particular set of the data are scattered in a constructive manner. This suggested that a smaller scale of analysis should be conducted to isolate and segregate the variables. In order to further examine the problem, each technology is evaluated separately. Literatures with multiple case studies on different type of biomass feedstock with consistent process condition are selected. This is to ensure higher consistency in terms of process conditions and equipments set up, in order for the analysis to focus more on the study of feedstock biomass element characteristic impact to respective process output.

4.5 Analysis of relation between feedstock element characteristics and syngas heat value in hydrocarbonization and gasification process

The first micro analysis is conducted based on Á.Murillo et al., (2015), which evaluated biomass gasification using three different types of biomass feedstock which consist of char, hydrochar and pristine olive waste. The main objective of their research was to evaluate the impact of hydrocarbonization (produces hydrochar) as pretreatment for biomass steam gasification processes as compared to traditional pyrolysis (produces char). Advantages of hydrocarbonization over conventional carbonization methods are no inert gas required, uses moderate temperature with water only, overall exothermal process, and can be applied on high moisture content biomass. Á.Murillo et al., (2015) proved that solid yield from hydrocarbonization approach (65.4 %) is higher than pyrolysis approach (24.7 %) which operated at optimum pyrolysis temperature of 600 °C. The gasification processes were conducted at atmospheric pressure with 2 g of feedstock. Inert gas,

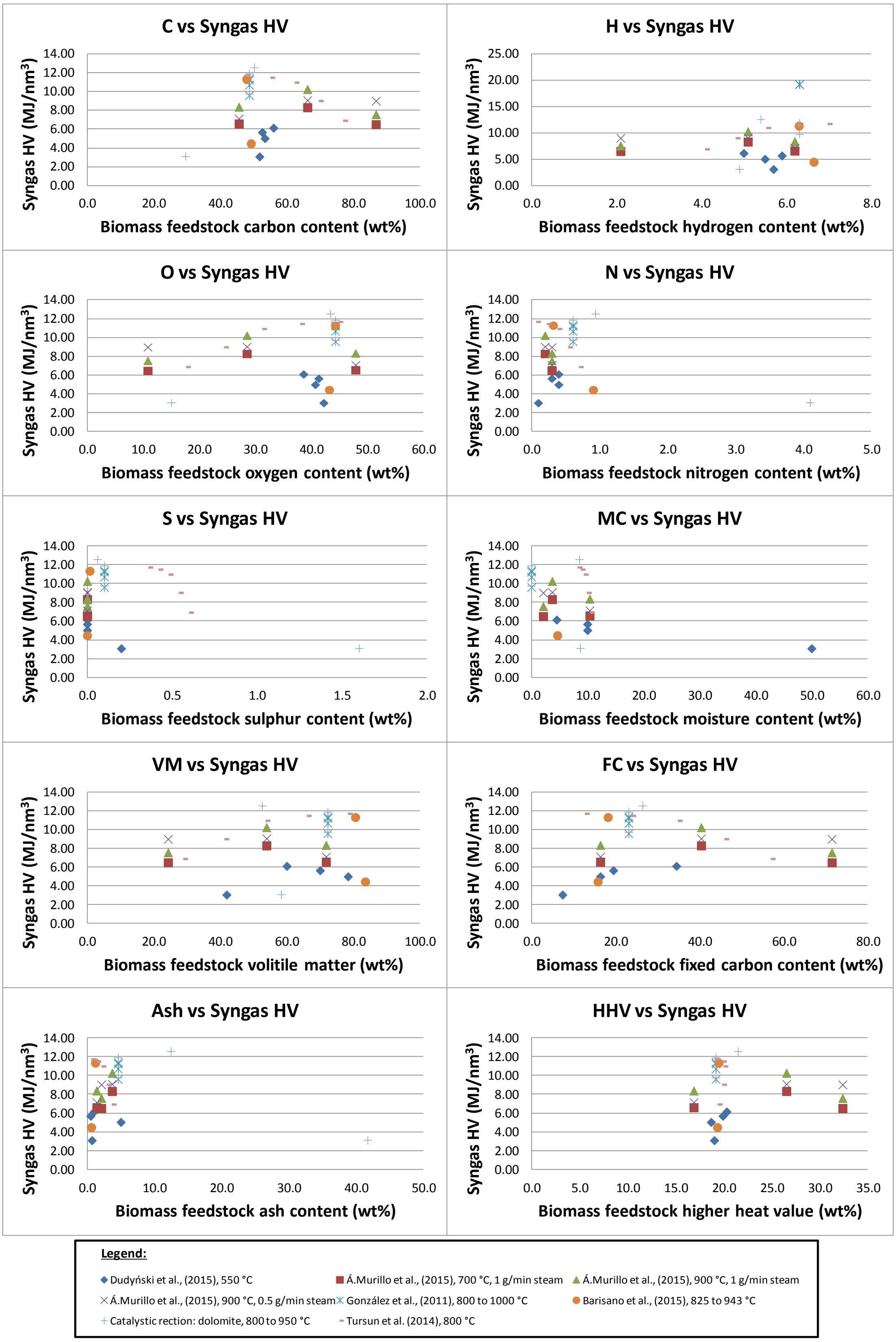


Figure 4- 1: Overall relation of biomass feedstock element characteristic with produced syngas HV

nitrogen flow at 10 cm^3/min was maintained for 1 hour to remove air in the system. The process was tested on different gasification temperature ranging from 700 °C to 900 °C and steam flow rate ranging from 0.5 to 1 g/min to investigate the impacts to the syngas composition and heating value. However, the relation between biomass feedstock element characteristic and produced syngas is yet to be studied. Since the reported literature involved three different feedstocks with distinguish element characteristics, the information is extracted for investigation. Three cases of experiment are extracted from the literature, Case A: gasification temperature at 700 °C with steam flowrate at 1 g/min, Case B: gasification temperature at 900 °C with steam flowrate at 1 g/min, and Case C: gasification temperature at 900 °C with steam flowrate at 0.5 g/min. The relation between feedstock element characteristics and syngas HV are plotted in Figure 4-2.

Based on the figure, there are some interesting findings that are worth to be analysed. First of all, the shapes of trend seemed to be consistent in all element characteristics analysis disregard of the different operation conditions. Difference in biomass feedstock element characteristics resulted difference in heating values of produced syngas. Under the influence of operating condition, the shape of the trend in Case A and Case B is almost identical, conversely, the produced syngas HV in Case B is a step higher than Case A. This is due to higher gasification temperature which favours production of hydrogen, and hence contributes to higher syngas HV. In Case C, the shape of the trends is slightly different in all the graphs. This may due to the difference in steam concentration in the reaction, thus affecting the equilibrium of the reactions and, hence producing different syngas concentration and altered the syngas HV. Nevertheless, due to limited diversity of biomass feedstock, the study on the overall trend of biomass element characteristic with respect to produced syngas heating value is yet to be concluded. The overall trends are unable to justify whether they are of linear relation or nonlinear quadratic relation as only three points of data are available. In addition, impact of sulphur content to heating value of produced syngas is unable to determine as all the biomass species used in the study are reported to have insignificant sulphur content. Thus, the available data is not sufficient to construct a strong element acceptance range for this particular process technology.

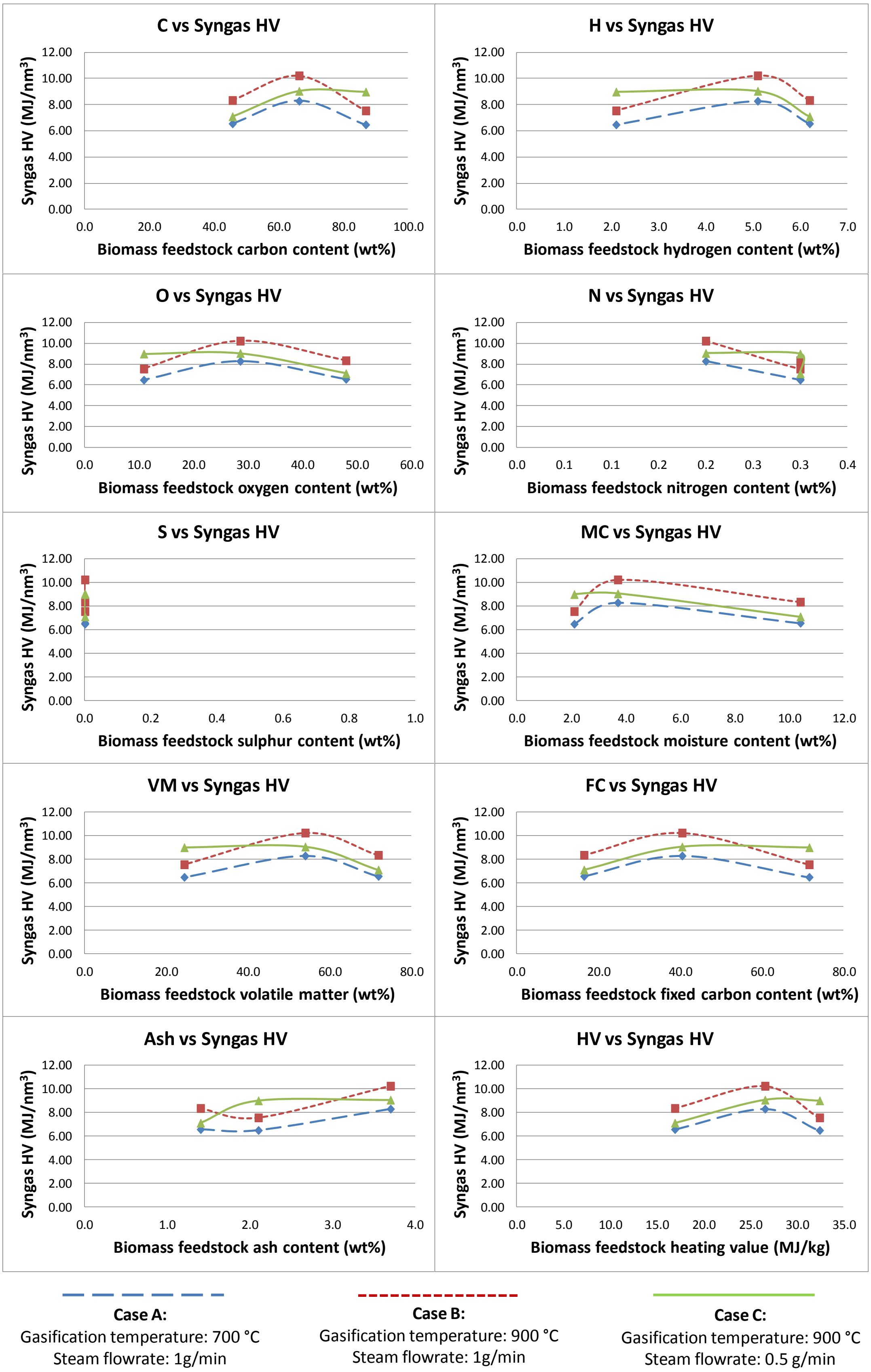


Figure 4- 2: Relation of biomass feedstock element characteristic with produced syngas HV based on Á.Murillo et al., (2015)

4.6 Analysis of relation between feedstock element characteristics and syngas heat value in biomass torrefaction and gasification process

The next analysis is conducted based on Dudyński et al., (2015) that studied the influence of torrefaction on syngas production and tar formation. Torrefaction is a pretreatment process to decompose the hemicellulose content within a woody biomass. Generally torrefaction is performed in moderate temperature of 200 °C to 300 °C with the absences of oxygen. Four biomass species were used in the study, namely Polish pellets, torrefied pellets from Portugal, South African pellets and Polish pine sawdust. A robust industrial fixed-bed gasifier designed to handle sawdust with variable moisture content and other pellet biomass, which was tested over 30,000 hours, is used in the study. The cuboid-shaped gasifier is capable to gasify up to 300 kg/h biomass. Air was used as oxidation agent. Gas cooler and gas probe were installed to condense tars and oil for composition analysis. Figure 4-3 shows the relation of biomass element characteristics with the produced syngas heating value.

From Figure 4-3, although the analysis consists of more variety of biomass feedstock, no significant trend of relation is observed. This may due to the inconsistency in operating condition in each case study. One of the objectives in Dudyński et al., (2015) research is to investigate operating parameters for each biomass feedstock, and optimise the operating condition for maximum liquid hydrocarbon production. Thus, the optimum operating conditions such as biomass feed rate, air stream flowrate, gasifying temperature and residence time are different in each biomass. Moreover, each biomass has its unique size and shape with is different from each other. This again fails to provide a fair comparison and analysis on the impact of feedstock element characteristics variation to process output.

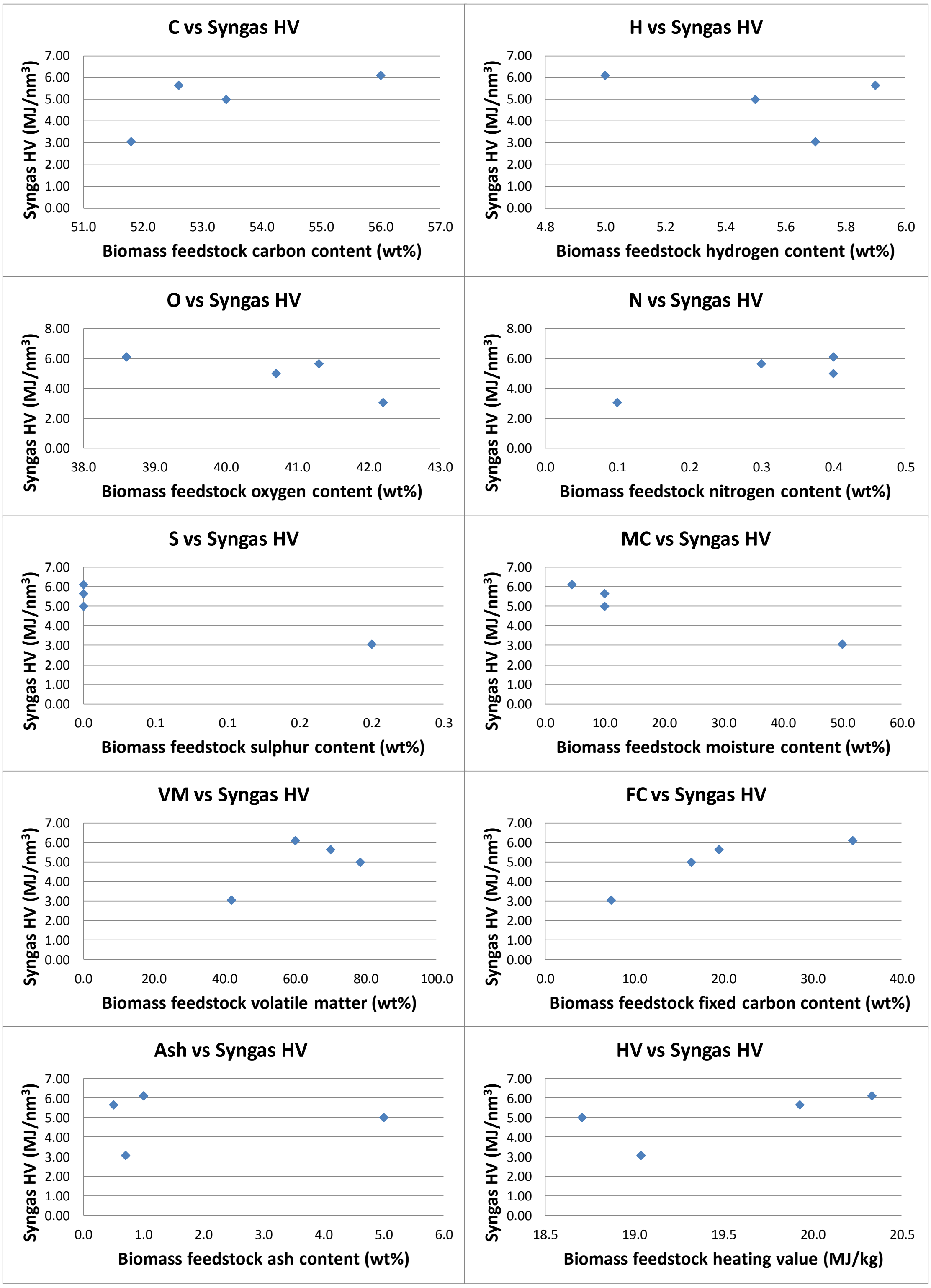


Figure 4- 3: Relation of biomass feedstock element characteristic with produced syngas heating value based on Dudyński et al., (2015)

4.7 Analysis of relation between feedstock element characteristics and syngas heat value and yield in catalytic steam co-gasification process

The next gasification technology to be evaluated is based on a catalytic biomass steam co-gasification as per Tursun et al., (2015). Two type of feedstock were used in the study, pine sawdust and bituminous coal. Calcined olivine was used as in-situ tar destruction catalyst as well as a heat carrier in the lab-scale external circulating radial-flow moving bed gasification system. Tursun et al., (2015) conducted several interesting studies on the system, including impact of biomass blending ratio, impact of pyrolyzer temperature, impact of gasifier temperature, and impact of steam to carbon mass ratio. Out of all the investigations, the study on the influence of biomass blending ratio to the process outcome is most related to the construction of element acceptance range for this technology. Variation of biomass blending ratio ranging from biomass 0 % to 100 % replicates various biomass feedstock element characteristics, thus allows the analysis and construction of relation between biomass feedstock element characteristics and process output. This is different from the previous analysis on Á.Murillo et al., (2015) and Dudyński et al., (2015), Tursun et al., (2015) fixed the operating parameters at 600 °C, 800 °C and 1.3 for pyrolyzer temperature, gasifier temperature and steam to carbon mass ratio respectively. This enhances the accuracy of the analysis. In addition, Tursun et al., (2015) not only investigated the heating value of produced syngas, but also the syngas yield. This gives an opportunity to evaluate the impact of feedstock element characteristics to syngas production yield. Figures 4-4 and 4-5 show the relation of the biomass feedstock element characteristics with respect to produced syngas heating value and syngas yield respectively.

Based on Figures 4-4 and 4-5, the relation of biomass feedstock element characteristic with respect to the gasification output is clearly shown. It is observed that feedstock element characteristics have polynomial relation to produced syngas heat value, while the feedstock element characteristics have linear relation to produced syngas yield. Increases of H, O, and VM; and decreases of C, N, S, MC, FC, Ash and HV improved produced syngas higher heating value and yield. The R-squared values of the graphs are also significantly higher as compared to the values in previous two studies. The uniform result indicates that consistency of process conditions has a high impact to

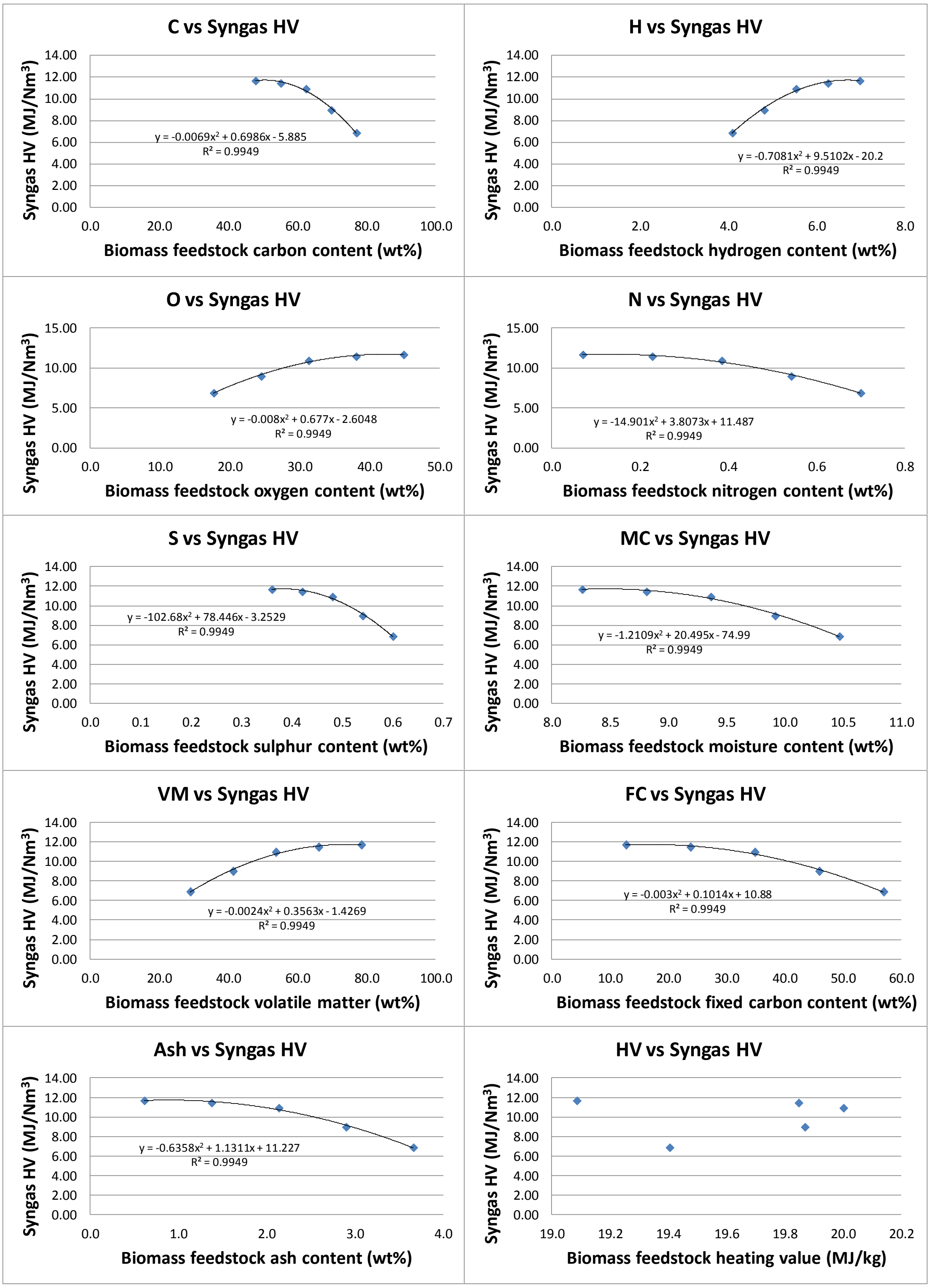


Figure 4- 4: Relation of biomass feedstock element characteristic with produced syngas heating value based on Tursun et al., (2015)

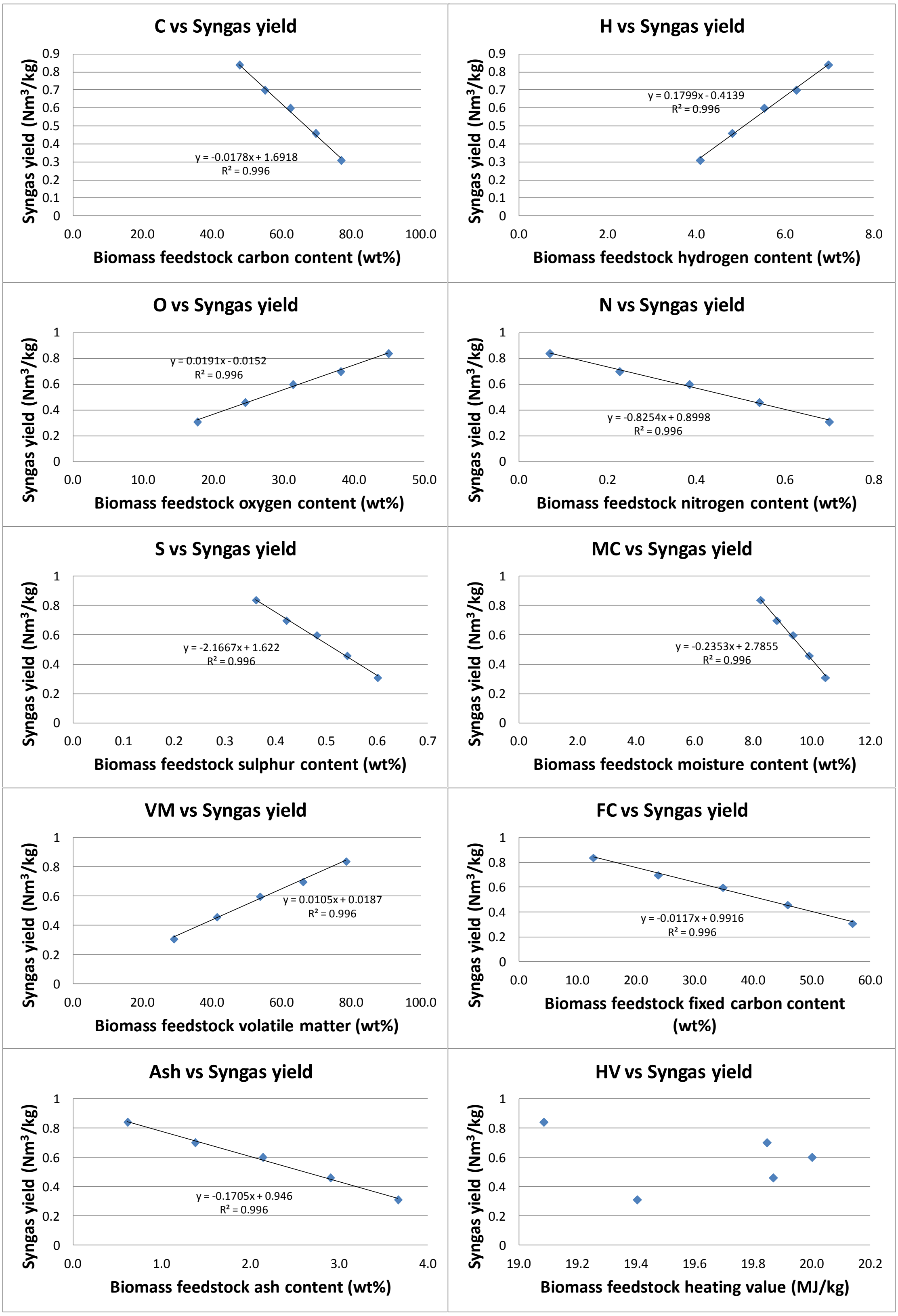


Figure 4- 5: Relation of biomass feedstock element characteristic with produced syngas yield based on Tursun et al., (2015)

the analysis. Thus, a controlled set of process condition is required to analyse the impact of feedstock element characteristic to process output. However, noted that in the graphs of biomass feedstock HV value versus syngas heating value (Figure 4-4) and biomass feedstock HV versus yield (Figure 4-5), no significant trends were observed. The scattered plots of graph may due to the fact that biomass HV value was estimated from the correlation as stated in Equation 4-1. The trend of the graphs will be more accurate provided that the HV value of the biomass is analysed via laboratory approach, such as using bomb calorimeter.

On the other hand, based on profound relations generated in Figures 4-4 and 4-5, further analysis can be conducted to compare and prioritise the level of impactness of each feedstock element characteristics towards the process performance. In other word, the analysis is conducted to determine fluctuation in which feedstock element characteristics will have the highest impact to the process performances, and hence to prioritise as the key elements. Figure 4-5 shows linear relations between feedstock element characteristic and syngas yield. In general, the impact of the x-axis value to the y-axis value is highly dependence on the slope coefficient in linear relations. Thus, in order to justify which element characteristics has the most to least impact to the process performance, the "m" value or the slope coefficient of each graphs are compared. However, this method is not applicable in non-linear relations such as in Figure 4-4. Nevertheless, depending on the case, feasible assumption can be constructed to simplify the problem. For instance, although a non-linear relation is fit well in Figure 4-4, however, linear equations can be used to conduct the analysis of the level of impactness of the feedstock element characteristics to the syngas HV as long as the R^2 value is within an acceptable range (above 0.85). Figure 4-6 plotted the linear relation of the same data presented in Figure 4-4. The R^2 value is found to be 0.88 in all the graphs which is in the acceptable range, except for HV vs Syngas HV due to the same reason as discussed previously.

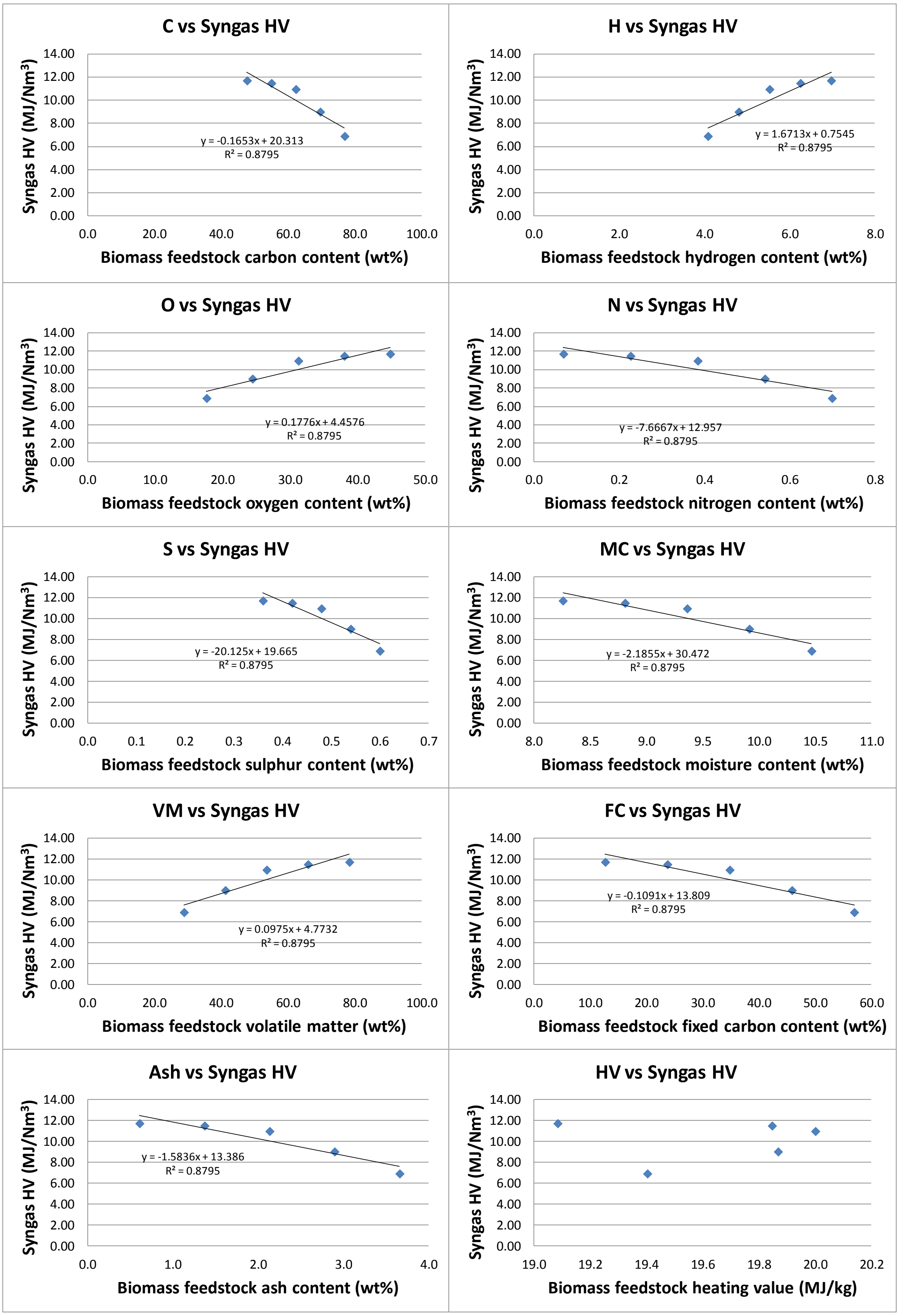


Figure 4- 6: Linear relation of biomass feedstock element characteristic with produced syngas heating value based on Tursun et al., (2015)

Based on Figures 4-5 and 4-6, the slope coefficient is extracted from each graph and tabulated in Table 4-3 and prioritised from 1 to 9, 1 being the highest impact to the process performances due to higher slope coefficient. The result shows that in both cases of impact to syngas yield and HV, sulphur content has the highest impact to the process outputs, followed by nitrogen content, moisture content, hydrogen content, ash content, oxygen content, carbon content, fixed carbon, and volatile matter. This provides a good understanding on the impact of each properties fluctuation and a guideline prioritise the biomass selection criteria. Nonetheless, this is only proved to be application in the technology proposed by Tursun et al., (2015). Further analysis is required to determine the impactness of each element characteristics in biomass gasification process.

Table 4- 3: Prioritising key element based on slope coefficient

Priority	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Impact to syngas yield	**S** (2.17)	**N** (0.83)	**MC** (0.24)	**H** (0.18)	**Ash** (0.17)	**O** (0.02)	**C** (0.02)	**FC** (0.01)	**VM** (0.01)
Impact to syngas HV	**S** (20.1)	**N** (7.67)	**MC** (2.19)	**H** (1.67)	**Ash** (1.58)	**O** (0.18)	**C** (0.17)	**FC** (0.11)	**VM** (0.10)

4.8 Discussion and construction of element acceptance range

Based on the analysis above, there is still gap to construct a general relation between feedstock element characteristics and syngas heat value for all biomass gasification technologies. Most of the literatures have yet to analyse the impact of biomass feedstock in term of element characteristic variation. In addition, differences in operating conditions are significantly affecting the process outcome, which further complicates the process to conclude the impact of feedstock element characteristics to process outputs. Obtaining experiment data from literatures for the analysis often contains inconsistency or uncertainties in the comparison due to discrepancy in process parameters. Nonetheless, the analysis is proven to be possible, provided that the literature used has sufficient data and consistency in operating condition. Once the impact of feedstock element characteristics to process performance is verified, element acceptance range for that particular technology can be constructed.

For example, by assuming the gasification technology proposed by Tursun et al. (2015) is implemented in biomass industry and the supply chain network. Assuming the targeted syngas HV is in the range of 9.00 MJ/Nm^3 to 10.95 MJ/Nm^3. Conventionally based on the research conducted by Tursun et al. (2015), the feedstock option should only consist of biomasses mixture (sawdust and bituminous coal) ranging from 25 wt% to 50 wt% of sawdust. All other alternative biomass species are not considered in the system unless a major process equipment modification or study is involved. However, according to the analysis conducted on the relation between biomass feedstock element characteristics and syngas HV as per Figure 4-4, and the concept of element targeting, the feedstock properties requirements can be back calculated based on the targeted output as shown in Figure 4-7. Upper and lower boundaries for respective element characteristics are identified and element acceptance range is constructed based on the combination of this information, as shown in Figure 4-8. HV is excluded in this study due to the inconclusive relation as shown in Figure 4-4. Note that the proposed element acceptance range is only dedicated to the targeted output of 9.00 MJ/Nm^3 to 10.95 MJ/Nm^3 via the proposed equipment setup and operating conditioned by Tursun et al. (2015). Any changes of equipment or operating conditions will affect the element acceptance of the technology.

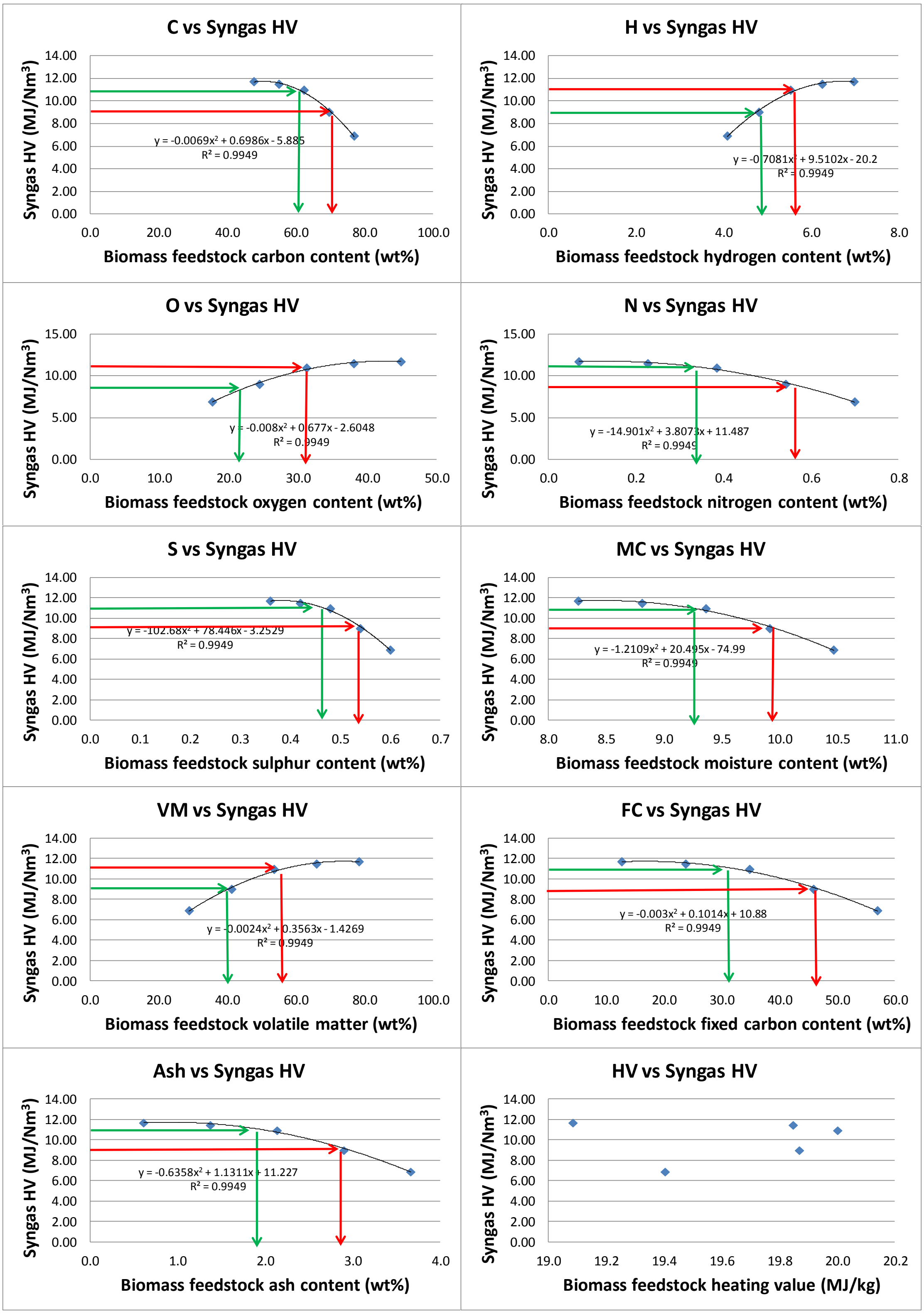


Figure 4- 7: Construction of element acceptance range based on targeted syngas output of 9.00 MJ/Nm^3 to 10.95 MJ/Nm^3

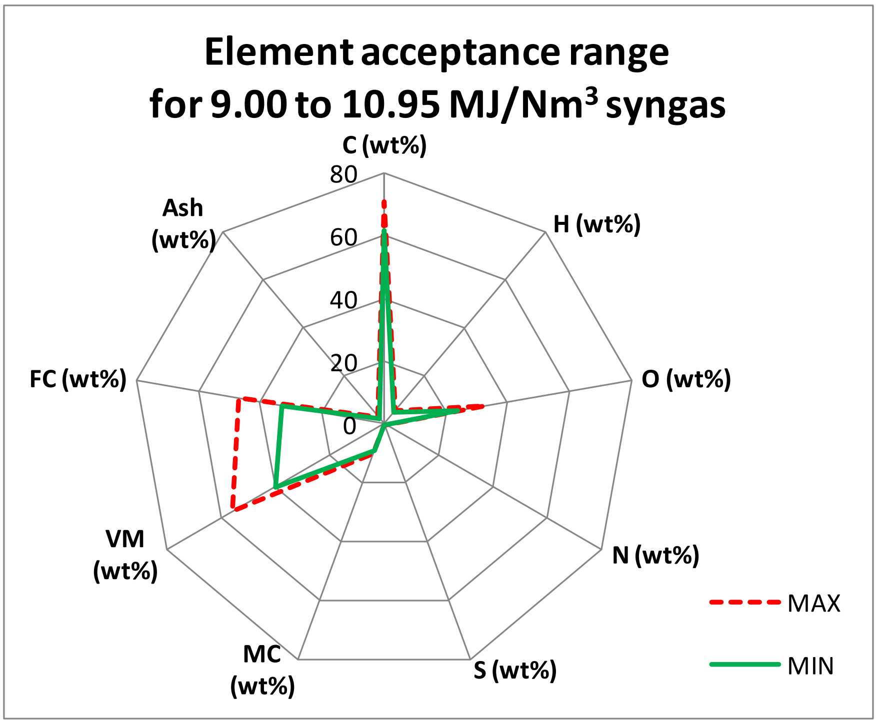


Figure 4- 8: Element acceptance range for Tursun et al., (2015) catalytic co-gasification technology

The concept of element targeting suggested that the feedstock selection criteria are based on the proposed element acceptance range in Figure 4-8, instead of biomass species, which are sawdust and bituminous coal in this case. Alternative biomass species can be integrated into this technology with similar targeted output of syngas range in between 9.00 MJ/Nm^3 and 10.95 MJ/Nm^{3}as long as the feedstock element characteristics are within the element acceptance range. The integration of biomass mixture is enabled with the assumption that the element characteristics of alternative biomass mixtures can be predicted based on individual biomass properties via linear relation with respect to the mass ratio as discussed in Chapter 3. This allows the feedstock selection of the process to be more flexible as long as the element characteristics of alternative biomass are known and the feedstock mixture fulfilled the element acceptance range of the technology. Nevertheless, this assumption on the biomass properties prediction based on mass ratio is a fairly new concept. Thus, this will be verified in the next chapter via laboratory analytical test to ensure the feasibility of implementation.

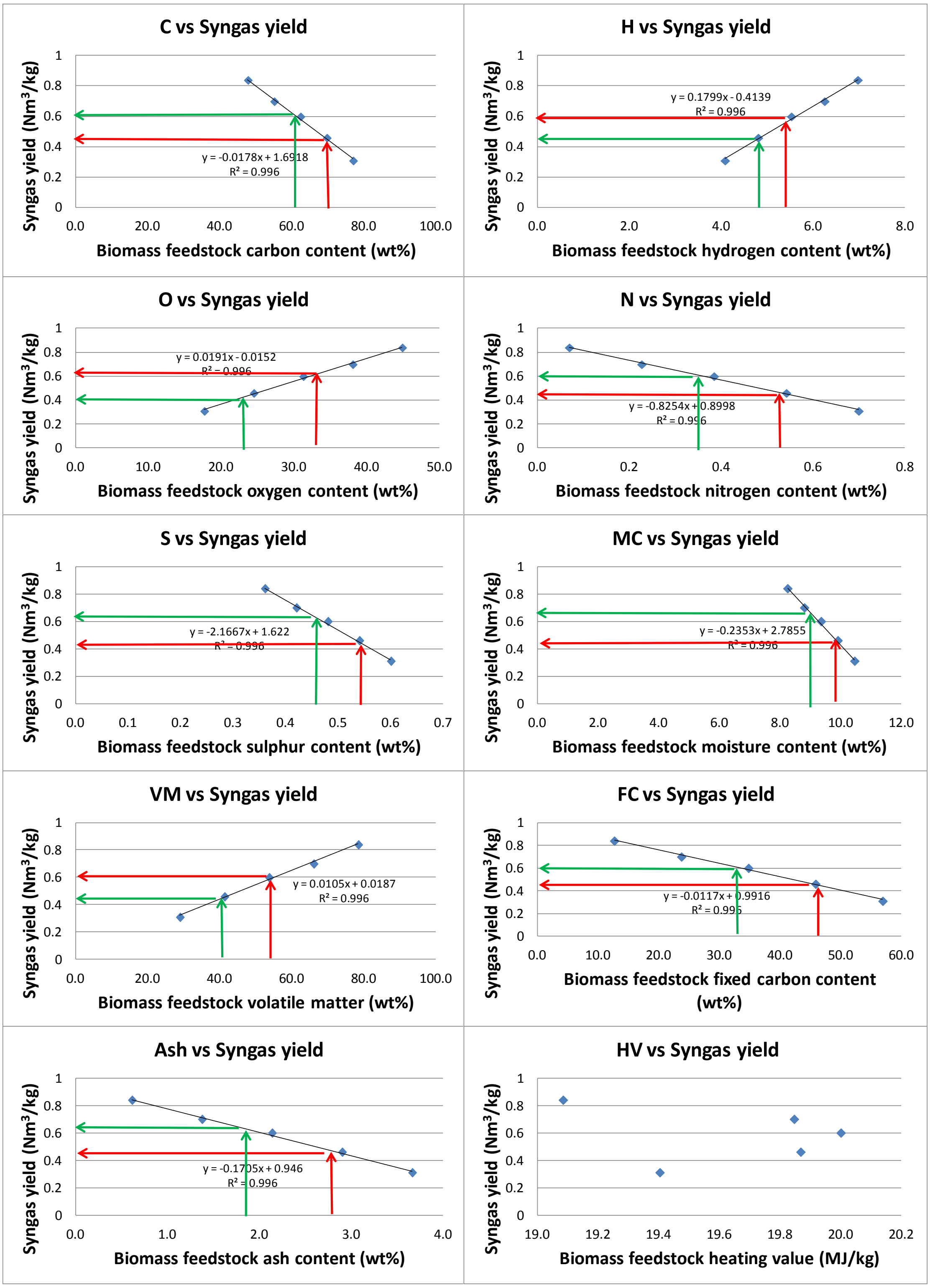


Figure 4- 9: Estimation of syngas production yield based on proposed element acceptance range

Based on element acceptance range in Figure 4.8, the syngas production yield can also be predicted. The estimation is based on the proposed relation in Figure 4-5, where the technology yield range is back calculated as shown in Figure 4-9. The result shows that in average, the syngas production yield is estimated to be in the range of 0.44 Nm^3/kg to 0.65 Nm^3/kg. Thus, for this example, the syngas production yield is estimated to be in the range of 0.44 Nm^3/kg to 0.65 Nm^3/kg with the HV of 9.00 MJ/Nm^3 and 10.95 MJ/Nm^3 provided that biomass feedstock properties are within the element acceptance range in Figure 4-8.

Based on the example above, it is shown that element acceptance range for biomass technology can be constructed based on literatures to improve the flexibility in biomass selection. The approach enables consideration of other alternative biomass species to be used as potential feedstock with minimum modification effort, provided that the element characteristics of the biomass are known. As long as the biomass or biomass mixture is within the element acceptance range, then the process outcome can be estimated within a desired range. Similar to the biomass properties prediction method discussed earlier, the assumption of process outputs prediction based on element acceptance range will be verified in the next chapter via laboratory experiment to study the relation between process performances and feedstock properties tolerances. The element acceptance range for the technology is based on the targeted output value of the process. Smaller targeted syngas heating value range or yield range will result in smaller element acceptance range and hence lower the technology flexibility in terms of biomass feedstock selection.

There are still challenges in constructing element acceptance range for biomass technology. For example in this case study, analysis of relation between biomass feedstock element characteristics and gasification process output based on literature review often requires more data to fill in the information gaps. Influence of variables in operating conditions further increases the complexity and difficulty. However, it is still possible to construct the element acceptance range for biomass technology based on literature data. In order to construct a systematic and accurate element acceptance range, the selection of literature need to be specific to minimise uncertainties and laboratory experiment as a potential alternative approach should be considered. The experiment is recommended to be conducted on high potential biomass technology, not limited to gasification process only and different variety of biomass species can be used as alternative feedstock to analyse the relation between feedstock element characteristic and process output. For a more practical research and development, the proposed analysis should be conducted after the optimum operating conditions is obtained for a particular biomass technology. With the introduction of element acceptance range in biomass technology, larger scale of implementation is deemed possible and the utilisation of alternative biomass will be enhanced. In addition, the approach enables integration of underutilised biomasses or alternative biomasses which are located nearer to the process plant, and hence reduce the raw material cost and transportation cost.

4.9 Conclusions

In this chapter, the relation between biomass feedstock element characteristics and biomass gasification outputs are investigated based on literature data. Based on the analysis, there is still existence of research gaps in order to generate a correlation to relate the biomass feedstock element characteristic to produced syngas heating value and yield. This is mainly due to different research focuses in gasification technologies, which each of them has unique optimum operating conditions and biomass feedstock species. Thus, analysis solely based on literature has its limitation especially in compiling gasification researches with similar technology set up and operating conditions in order to allow the analysis focus on the impact of biomass feedstock to process outputs. Besides feedstock element characteristics, operating conditions such as gasification temperature, feedstock to oxidation agent ratio, feedstock size, and process residence time also significantly affect the process outputs.

Later stage of the work proposed alternative method to conduct smaller scale analysis based on individual literature or technology for a better control over uncertainties in operating condition. This enables investigation to focus on relation between biomass feedstock element characteristics and the process outputs. Based on the small scale analysis conducted on several literatures, a pronouns relation between feedstock element characteristic and produced syngas heating value and yield are observed. This information was used to construct element acceptance range for biomass gasification technology to allow integration of alternative biomass into existing technology. Nonetheless, the accuracy of the relation also depends on the consistency of operating conditions in the literature. Thus, a controlled laboratory experiments to investigate the impact of feedstock element characteristics is recommended in order to construct high accuracy element acceptance range for biomass technologies. This will provides further verification on element targeting approach to allow integration of multiple biomass species into existing biomass system as long as the overall biomass feedstock element characteristics are within the element acceptance range.

This chapter has demonstrated the potential of integrating underutilised/alternative biomasses into existing process technologies based on literature via element targeting approach. However, feasibility of element targeting implementation is strongly based on two assumptions: i) prediction of biomass mixture properties based on mass ratio, and ii) prediction of biomass process outputs based on feedstock element characteristics tolerances. Both assumptions will be verified in following chapter via laboratory experiment work to solidify the concept of element targeting approach.

Chapter 5:
VERIFICATION OF ELEMENT TARGETING APPROACH VIA LABOROTORY EXPERIMENT: BIOMASS PYROLYSIS TECHNOLOGY

Continuing with the conclusion from previous chapter, the concept of element targeting approach has been proven feasible to be implemented into existing technology based on the available information from literatures. Nevertheless, previous chapters assumed that the properties of biomass mixture can be estimated based on pure biomass properties in a linear relation. In addition, verification of the element targeting concept based on current literatures in biomass technologies left some uncertainties in the analysis as the literatures do not focus on the impact of biomass feedstock element characteristics to technology performance. Thus, it is concluded that the experimental work catered specifically to examine the relations between biomass feedstock properties and process outputs are required to verify the concept of element targeting approach before further implementing the concept into biomass supply chain optimisation model. These verification steps are very important for the thesis to ensure the proposed concept is feasible to be implemented in real life as mathematical modelling and simulation can generate various results that sometimes only applicable in theoretical scenario. In this chapter, two verifications were conducted. First, the biomass mixture properties are analysed in laboratory and compared with the prediction value based on linear relation of pure biomass species. Second, a specific laboratory experimental procedure is created to investigate the relations between feedstock properties and process performances. Biomass pyrolysis technology is selected as case study due to its popularity and in parallel with biomass gasification. Besides, the production of bio-char and bio-oil as alternative fuels for energy generation via pyrolysis is one of the popular research fields for sustainable development.

5.1 Estimation of Biomass Mixture Properties

As suggested by element targeting approach in Chapter 3, the performance of biomass process technologies are assumed to be consistent as long as the feedstock properties are within the element acceptance range. This idea will provide the flexibility of feedstock selection by determining the best biomass ratio that is suitable for each process. Previous examples had assumed that mixture properties are linear to mass ratio of respective biomass species and their respective properties as shown in Equation 3-4. In order to ensure applicability of this concept in real life scenario, following section will verified the properties integration of biomass solid by analysing the element characteristics of biomass mixture and compared to the estimated properties based on the proposed correlation.

$$\begin{aligned} &Biomass\ mixture\ properties \\ &= (Biomass\ \text{"1"}\ fraction \times Bomass\ \text{"1"}\ properties) \\ &+ (Biomass\ \text{"2"}\ fraction \times Biomass\ \text{"2"}\ properties) + \\ &\ldots + (Biomass\ \text{"n" fraction} \times \text{Biomass "n" properties}) \end{aligned}$$

Reproduced from (3-4)

5.1.1 Methodology

In order to verify the assumption of linear relation in biomass properties prediction, several pure biomass species are collected and a series of their mixture at different mixing ratio are created. Element characteristics of each pure biomass and mixtures are determined via analytical test. The result obtained from the biomass mixtures are compared with the result predicted via proposed co-relation, such as Equation 3-4.

5.1.2 Materials and Procedures

Three biomass species (see Figure 5-1) were used in this research, i) Napier grass stem (NGS) collected from Crop For the Future Research Field, Semenyih, Selangor, Malaysia; ii) sago biomass (sago) from sago process plant effluent in Pusa, Sarawak, Malaysia; and iii) rice husk (RH) from rice processing mill in Sungai Besar, Selangor, Malaysia. Four biomass mixtures were created with the mass ratio as stated in Table 5-1.

Figure 5- 1: Napier grass steam, sago biomass, and rice husk

Table 5- 1: Biomass mixture ratio in sample preparation

Biomass	**NGS**		**Sago**		**RH**	
	Mass (g)	**%**	**Mass (g)**	**%**	**Mass (g)**	**%**
A	301.3	75.2	99.1	24.8	0	0
B	200.9	49.8	202.6	50.2	0	0
C	301.4	75.1	0	0	99.7	24.9
D	200.2	49.7	0	0	202.5	50.3

Three analyses were conducted to evaluate the element characteristics of biomass which are ultimate analysis, proximate analysis, and calorific analysis. Ultimate analysis identifies carbon content (C), hydrogen content (H), nitrogen content (N), sulphur content (S) and oxygen content (O) of biomass samples; while proximate analysis identifies moisture content (MC), volatile matter content (VM), fixed carbon content (FC), and ash content (ash). Calorific analysis determines the heat value of biomass.

Element characteristics of sago and rice husk are contributed by colleagues, Dr. Yuki and Mr. Isah respectively from University of Nottingham Malaysia Campus as shown in Table 5-2. The properties of pure NGS and biomass mixtures are determined via analytical equipments. Ultimate analyses were conducted by third party, University Putra Malaysia via CHN analyser and S analyser, where the remaining percentage is assumed to be oxygen content. Proximate analysis is conducted via Perkin Elmer Simultaneous Thermal Analyzer STA 6000 with the procedures suggested by Cassel and Menard (n.d.). Calorific analysis is conducted via bomb calorimeter- series 6100 by Parr Instrument Company. Analyses for each sample were repeated three times for consistency.

Table 5- 2: Element characteristic of sago and rice husk biomasses

Biomass	C (wt%)	H (wt%)	N (wt%)	S (wt%)	O (wt%)	MC (wt%)	VM (wt%)	FC (wt%)	Ash (wt%)	HHV (MJ/kg)
Sago	9.2	11.6	74.0	5.2	19.1	39.7	6.6	0.2	0.0	53.5
RH	9.3	1.8	81.5	16.8	18.1	51.6	6.0	1.0	0.3	41.1

5.1.3 Results and discussions

Table 5-3 summaries the element characteristic of pure NGS and biomass mixtures obtained from the analytical results. The table tabulated all three different tests on each sample and their average values. Figure 5-2 presented the element characteristics of the three pure biomasses presented in the form of radar charts.

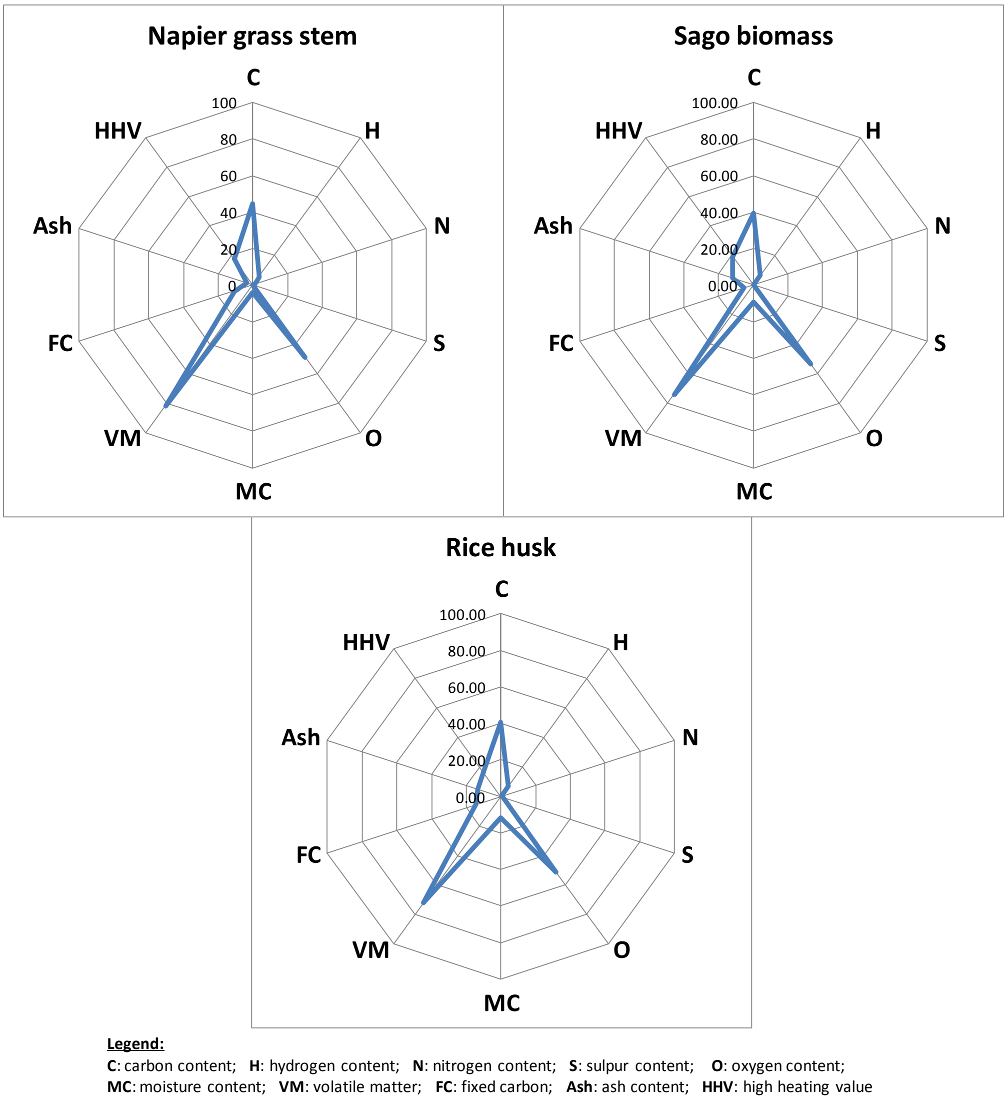


Figure 5- 2: Element characteristics for NGS, Sago and RH

Table 5- 3: Element characteristic of NGS and biomass mixtures

Biomass		C (wt%)	H (wt%)	N (wt%)	S (wt%)	O (wt%)	MC (wt%)	VM (wt%)	FC (wt%)	Ash (wt%)	HHV (MJ/kg)
NGS	1	44.5	5.2	1.0	0.1	49.2	4.2	77.7	14.5	3.6	17.4
	2	44.4	5.6	0.9	0.0	49.2	3.9	79.1	14.2	2.9	17.7
	3	44.7	5.7	0.8	0.1	48.7	4.6	88.0	3.9	3.5	17.8
	avg	**44.5**	**5.5**	**0.9**	**0.1**	**49.0**	**4.3**	**81.6**	**10.8**	**3.3**	**17.6**
A	1	43.6	5.5	0.7	0.0	50.3	5.6	87.8	3.5	3.1	17.0
	2	43.6	5.7	0.6	0.0	50.0	6.2	87.1	3.6	3.0	17.0
	3	43.7	5.7	0.7	0.1	49.8	6.2	87.1	2.9	3.9	17.0
	avg	**43.6**	**5.7**	**0.6**	**0.0**	**50.0**	**6.0**	**87.3**	**3.3**	**3.3**	**17.0**
B	1	41.3	6.1	0.3	0.1	52.2	8.9	86.9	2.2	2.1	16.5
	2	41.3	6.1	0.4	0.1	52.1	10.1	86.5	3.6	0.0	16.5
	3	41.2	6.2	0.3	0.1	52.2	8.5	87.3	2.9	1.3	16.5
	avg	**41.3**	**6.1**	**0.4**	**0.1**	**52.2**	**9.2**	**86.9**	**2.9**	**1.1**	**16.5**
C	1	43.8	5.4	0.7	0.1	50.0	5.0	86.2	3.3	5.5	17.4
	2	43.7	5.6	0.7	0.0	50.0	5.6	86.3	3.1	5.1	17.5
	3	43.7	5.6	0.7	0.1	50.0	5.1	86.0	3.2	5.8	17.0
	avg	**43.7**	**5.5**	**0.7**	**0.1**	**50.0**	**5.2**	**86.2**	**3.2**	**5.4**	**17.3**
D	1	41.8	5.6	0.6	0.0	52.0	6.3	83.5	1.8	8.4	16.5
	2	41.9	5.6	0.6	0.1	51.8	5.7	84.4	1.5	8.4	16.6
	3	41.9	5.6	0.6	0.1	51.9	6.3	83.5	1.8	8.4	16.6
	avg	**41.9**	**5.6**	**0.6**	**0.1**	**51.9**	**6.1**	**83.8**	**1.7**	**8.4**	**16.6**

Based on the assumption discussed in Chapter 3, element targeting suggested that the biomass mixture properties can be estimated based on the pure biomass element characteristics and the mixing ratio. In order to verify the assumption, Table 5-4 tabulates the estimated biomass mixture properties for samples A, B, C, and D calculated based on Equation 3-4, where the mixing ratio is based on Table 5-1; and the average value of the actual biomass element characteristics obtained from analytical studies. Standard deviations of both set of data are also tabulated in Table 5-4. Figure 5-3 shows the difference of the estimated value and the actual value in radar chart.

Table 5- 4: Comparison of estimated and actual biomass element characteristics

Biomass		C (wt%)	H (wt%)	N (wt%)	S (wt%)	O (wt%)	MC (wt%)	VM (wt%)	FC (wt%)	Ash (wt%)	HHV (MJ/kg)
A	Estimated	43.3	5.8	0.7	0.0	50.1	5.5	79.7	9.5	5.4	18.0
	Actual	43.6	5.7	0.6	0.0	50.0	6.0	87.3	3.3	3.3	17.0
	Standard deviation	**0.20**	**0.08**	**0.05**	**0.00**	**0.07**	**0.37**	**5.39**	**4.33**	**1.44**	**0.70**
B	Estimated	42.1	6.1	0.5	0.0	51.3	6.7	77.8	8.0	7.5	18.4
	Actual	41.3	6.1	0.4	0.1	52.2	9.2	86.9	2.9	1.1	16.5
	Standard deviation	**0.58**	**0.07**	**0.14**	**0.02**	**0.62**	**1.72**	**6.46**	**3.64**	**4.54**	**1.31**
C	Estimated	43.6	5.8	0.8	0.3	49.6	6.1	79.3	11.8	5.8	17.4
	Actual	43.7	5.5	0.7	0.1	50.0	5.2	86.2	3.2	5.4	17.3
	Standard deviation	**0.11**	**0.22**	**0.07**	**0.15**	**0.31**	**0.63**	**4.87**	**6.07**	**0.22**	**0.06**
D	Estimated	42.6	6.1	0.7	0.5	50.1	8.0	76.9	12.7	8.3	17.1
	Actual	41.9	5.6	0.6	0.1	51.9	6.1	83.8	1.7	8.4	16.6
	Standard deviation	**0.52**	**0.40**	**0.03**	**0.29**	**1.23**	**1.35**	**4.87**	**7.80**	**0.11**	**0.37**

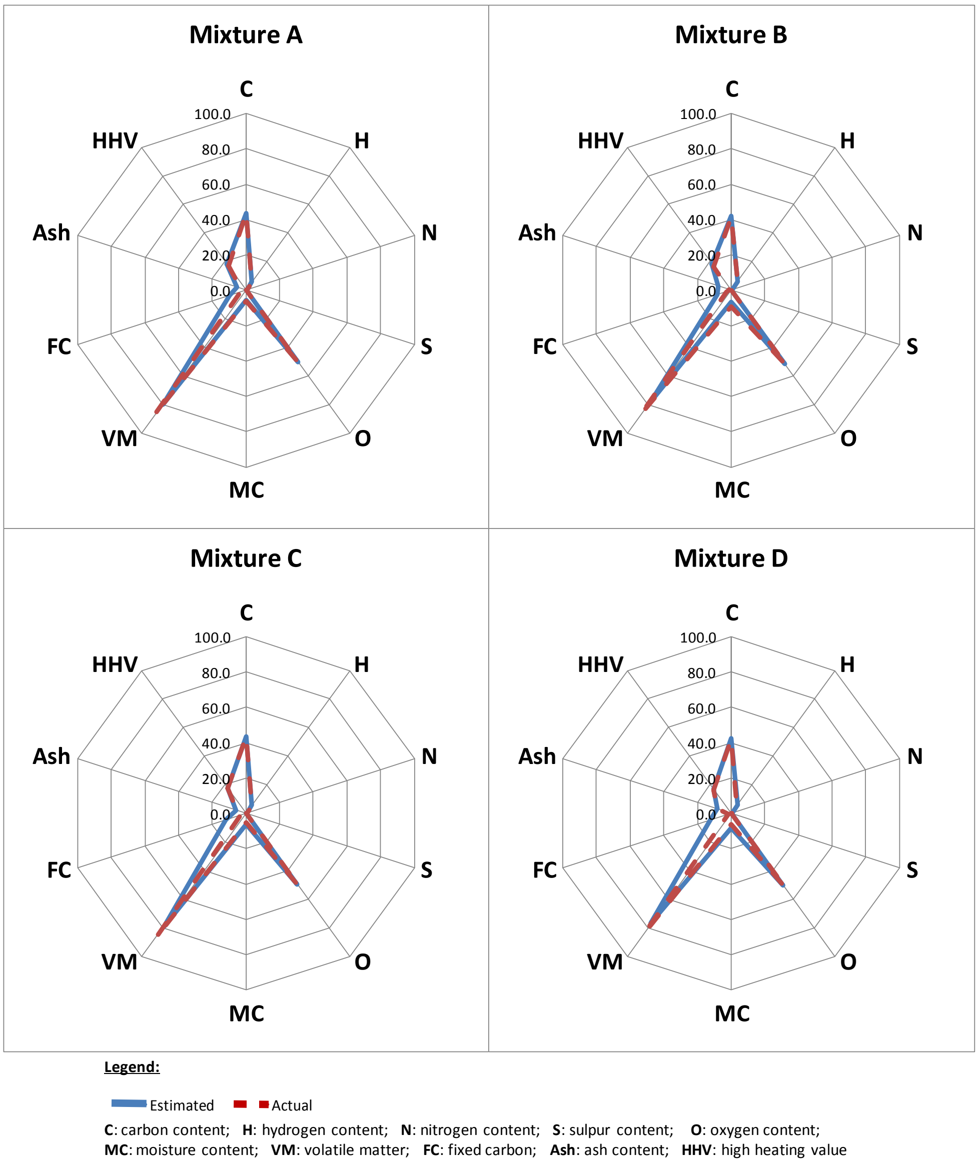


Figure 5- 3: Estimated and actual element characteristics of biomass mixtures

As shown in the comparison, both the estimated values and the actual values obtain from laboratory is comparable with relatively small difference. The standard deviations are generally less than 2.0, with some exceptions in volatile matter and fixed carbon content. The huge difference is suspected due to the long storage period of sago and rice husk biomass. Nevertheless, the biggest standard deviation of 7.80 is calculated based on the comparison between the actual and the estimated fixed carbon of sample D, 50 wt% NGS and 50 wt% rice husk. Involvement of more biomass species and mixing ratio will further strengthen the concept verification.

Nevertheless, based on the analysis conducted in this section, the results have shown that the deviation between estimated element characteristics value and the actual value is within the acceptable range (less than 10% in standard deviation). Thus, it can be concluded that the properties of biomass mixture can be predicted in a linear relation based on the mass ratio of pure biomasses and the element characteristics of pure biomasses. For example, assuming that a biomass mixture of 50 wt% NGS, 25 wt% sago, and 25 wt% RH, the overall mixture properties can be estimated via Equation 3-4 (illustrated in Figure 5-4).

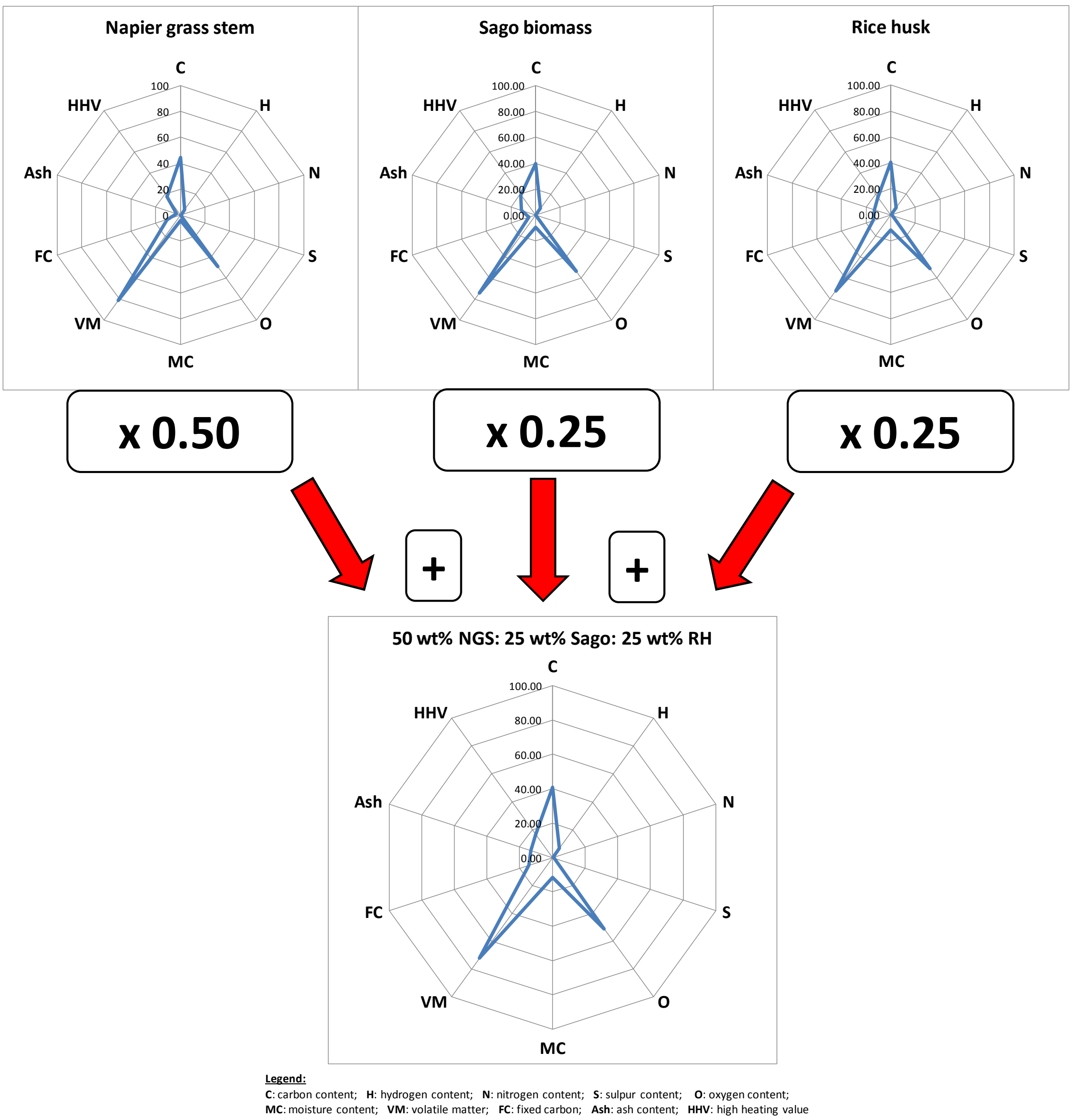


Figure 5- 4: Illustration of biomass mixture element characteristics prediction

As discussed in Chapter 3, two main assumptions in element targeting approach are: i) biomass mixture element characteristics are in linear relation with the mass ratio of biomass and their respective properties; ii) no major process fluctuation in biomass technologies as long as the feedstock is within element acceptance range. The findings in this section have verified the first assumption where biomass mixture properties are found to be in the linear relation with mass ratio and the pure biomass element characteristics. This suggested that the proposed Equation 3-4 is applicable in biomass supply chain optimisation model as a platform to determine the optimum feedstock ratio to ensure that the feedstock element characteristics are within the respective technology element acceptance range. Upon verification of the biomass selection platform, next section will verify the relation between biomass feedstock element characteristics and process outputs to determine technology feedstock tolerances. Both verification works on biomass selection platform and technology tolerances will provide a strong foundation for element targeting approach in mathematical optimisation model, such that biomass supply chain network can be optimised by integrating alternative or underutilised biomasses into the system without compromising the process performances.

Before moving to the next section to investigate the element acceptance range for biomass technology, a small verification of HHV prediction model, Equation 4-1 proposed by Nhuchhen and Salam (2012) is cross-checked with the analysis result obtained from this studies. Table 5-5 shows the actual value of HV of the samples obtained from analytical test and the predicted value based on the correlation. Both percentage error and standard deviation for most of the comparison are found to be within the acceptable range (less than 10%). This suggests that the correlation proposed by Nhuchhen and Salam (2012) is applicable in this study, thus can be used in case of unavailability of biomass HV data.

$$HV = 20.7999 - 0.3214 \times \frac{VM}{FC} + 0.0051 \times \left(\frac{VM}{FC}\right)^2 - 11.2277 \times \frac{Ash}{VM} + 4.4953\left(\frac{Ash}{VM}\right)^2 - 0.7223 \times \left(\frac{Ash}{VM}\right)^3 + 0.0383 \times \left(\frac{Ash}{VM}\right)^4 + 0.0076 \times \frac{FC}{Ash}$$

Reproduced from (4-1)

Table 5- 5: Biomass HV value comparison

Biomass	Actual HV (MJ/kg) (from analysis)	Predicted Value (MJ/kg) (Nhuchhen and Salam, 2012)	Percentage error (%)	Standard deviation
NGS	17.6	18.2	3.4	0.4
A	17.0	15.5	9.1	1.1
B	16.5	15.6	5.3	0.6
C	17.3	15.1	12.4	1.5
D	16.6	16.3	1.7	0.2

5.2 Biomass technology element acceptance range

Section above has presented the work to verify the concept of element characteristics estimation for biomass mixture, this section focuses on the concept verification of the element acceptance range for biomass technology. As discussed earlier, it is one of the core assumptions in element targeting approach which stated that the performance of biomass process technology will remained consistent provided that the feedstock is within the element acceptance range. Here, a laboratory experiment was conducted to verify this concept. The main objective is to evaluate the technology tolerances in handling different biomass feedstock while remained consistent in performance. Biomass gasification and pyrolysis are two popular conversion technologies in bio-resources to produce bio-fuel and bio-chemical. Chapter 4 has discussed the validation of element acceptance range of gasification process via literature review. Different type of process technology, namely biomass pyrolysis is selected as the case study for this chapter. This creates an opportunity to validate the concept in multiple technologies via both literature based and experimental based approach.

5.2.1 Biomass Pyrolysis and its Current Limitations

Pyrolysis process is an established technology to convert biomass into bio-char or bio-oil for energy production. Detailed explanations of biomass pyrolysis were discussed in Section 3.2.1. Similar to the situation of biomass gasification technologies, the current research and development of biomass pyrolysis has little effort in exploring the flexibility to integrating multiple alternative biomasses into the existing technologies. Overly focus on development of pyrolysis process based on specific biomass species (main stream biomass) restricts the feedstock selection and utilisation. Hence, this creates challenges for biomass supply chain management to ensure consistency in biomass resource supply and limits the potential to industrialise the biomass pyrolysis technology and enhance its implementation into current supply chain system where technology feedstock is restricted to dedicated biomass species.

5.2.2 Objectives

The main objective of this chapter is to verify the concept of element targeting in biomass pyrolysis technology, especially the evaluation of the element acceptance range concept. As concluded in previous chapter, verification based on literatures raised uncertainty issue as each of the literature researches were not designed and produced specifically to investigate the relation between biomass feedstock element characteristics and technology performance. Thus, this chapter is essential to validate the concept by using laboratory scale pyrolysis reactor. Multiple type of biomass feedstocks were feed into fixed bed pyrolysis reactor and the process outcomes were compared with the fluctuation of feedstock element characteristics. This provides a good platform to determine the tolerance of the technology on feedstock fluctuation, and to construct the element acceptance range for the technology.

5.2.3 Methodology of element targeting approach verification and construction of element acceptance range

In order to construct the relations between each biomass feedstock element characteristics and process output, each technology is required to be assessed with various types of biomass feedstock in order to replicate various feedstock properties. Equipment setup and operating conditions were remained constant throughout the experiment. Fluctuations in feedstock element characteristic are used to compare with the process outputs in order to study their respective impact. Based on the comparison and analysis, element acceptance range is constructed to reflect the flexibility of respective technology to feedstock properties fluctuation. There are several options to formulate a variety of biomass feedstock properties with unique element characteristics, such as using different biomass species and mixture of biomasses at different mixing ratio.

5.2.4 Laboratory experiment: Semi batch fixed bed pyrolysis

For this scope, collaboration with Mr. Isah, PhD student from Crop For The Future and University of Nottingham Malaysia Campus was engaged. A semi batch fixed bed pyrolysis reactor was used for the concept verification purpose. Similar equipment set up and operating conditions used in Napier grass stem development for bio-oil production were also applied in this case study. Figures 5-5 shows the experiment set up and equipments in block diagram and the pictures of equipments.

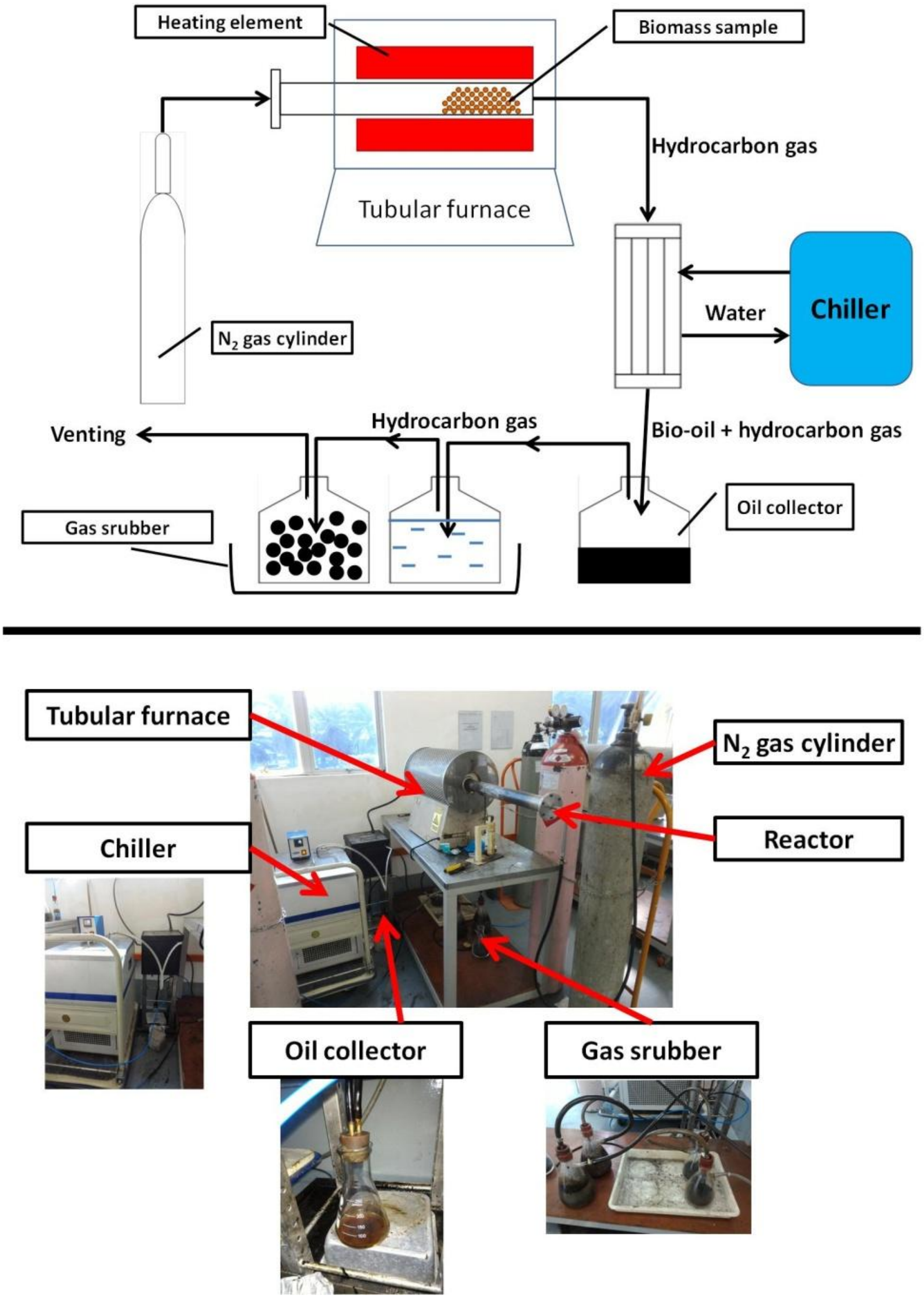


Figure 5- 5: Experiment set up and equipments

5.2.5 Materials and procedures

Three species of biomasses were used in this set of work, Napier grass stem (NGS), sago biomass (Sago), and rice husk (RH). These are the same biomasses used in Section 5.1 on the element characteristics analysis. All materials were oven dried upon received according to BS EN 14774-1 standard to prolong the storage life spend. In order to replicate the various feedstock element characteristics, a total of five different biomass feedstocks were used in the experiment, which consist of pure NGS and mixture of NGS, sago and RH. Table 5-6 tabulated the samples and their mixing ratio. Noted that the biomass mixture used in this study (sample 2 to 5) are identical to the sample used in the biomass mixture properties estimation in previous section (sample A to D in Table 5-1).

Table 5- 6: Biomass mixture ratio in sample preparation

Biomass	NGS		Sago		RH	
	Mass (g)	%	Mass (g)	%	Mass (g)	%
1	400.0	100.0	0	0	0	0
2	301.3	75.2	99.1	24.8	0	0
3	200.9	49.8	202.6	50.2	0	0
4	301.4	75.1	0	0	99.7	24.9
5	200.2	49.7	0	0	202.5	50.3

Fixed bed tubular reactor as shown in Figure 5-5 was used in this study. The pyrolysis process was conducted under inert atmosphere with nitrogen gas flow at 5 l/min. Approximately 100 g of biomass was fed into the reactor in each run. The reactor and biomass were heated up to 600 °C at the ramping rate of 30 °C/min, and the temperature was held for 1 hour. Volatiles generated were cooled rapidly in condenser with chill water at 3 °C, which was controlled by the chiller. Crude bio-oil produced was collected in the oil collector. Crude bio-oil yield and char yield were calculated based on Equation 5-1 and Equation 5-2. Due to the relatively low heating value of crude bio-oil produced (present of moisture, acids and other substances), the produced oil was mixed with industrial-grade-diesel to produce bio-diesel. The mixing ratio was set at approximately 70 wt% and 30 wt% of diesel and crude bio-oil respectively. Then, the higher heating value (HHV) of bio-diesel was determined via bomb calorimeter - series 6100 by Parr Instrument Company. Experiment for each samples were replied 3 times to ensure consistency.

$$crude\ bio\text{-}oil\ yield\ (wt\%) = \frac{crude\ bio\text{-}oil\ collected\ (g)}{total\ biomass\ feedstock\ (g)} \times 100\% \tag{5-1}$$

$$char\ yield\ (wt\%) = \frac{char\ collected\ (g)}{total\ biomass\ feedstock\ (g)} \times 100\% \tag{5-2}$$

5.2.6 Results and discussions

Considering the biomass feedstock used in this study and the biomass sample used in the previous study in Section 5.1 are the same, the same element characteristics of the sample are applicable for this case. Table 5-7 tabulated the actual element characteristics of the biomass feedstocks obtained from laboratory analysis. Maximum and minimum values of each element characteristics are also tabulated to illustrate the upper and lower range of feedstock properties to be evaluated in this study. The fluctuation in feedstock properties are compared to the fluctuation of process outputs performance, including bio-oil yield, bio-char yield and bio-diesel HHV.

Table 5- 7: Element characteristic of NGS and biomass mixtures

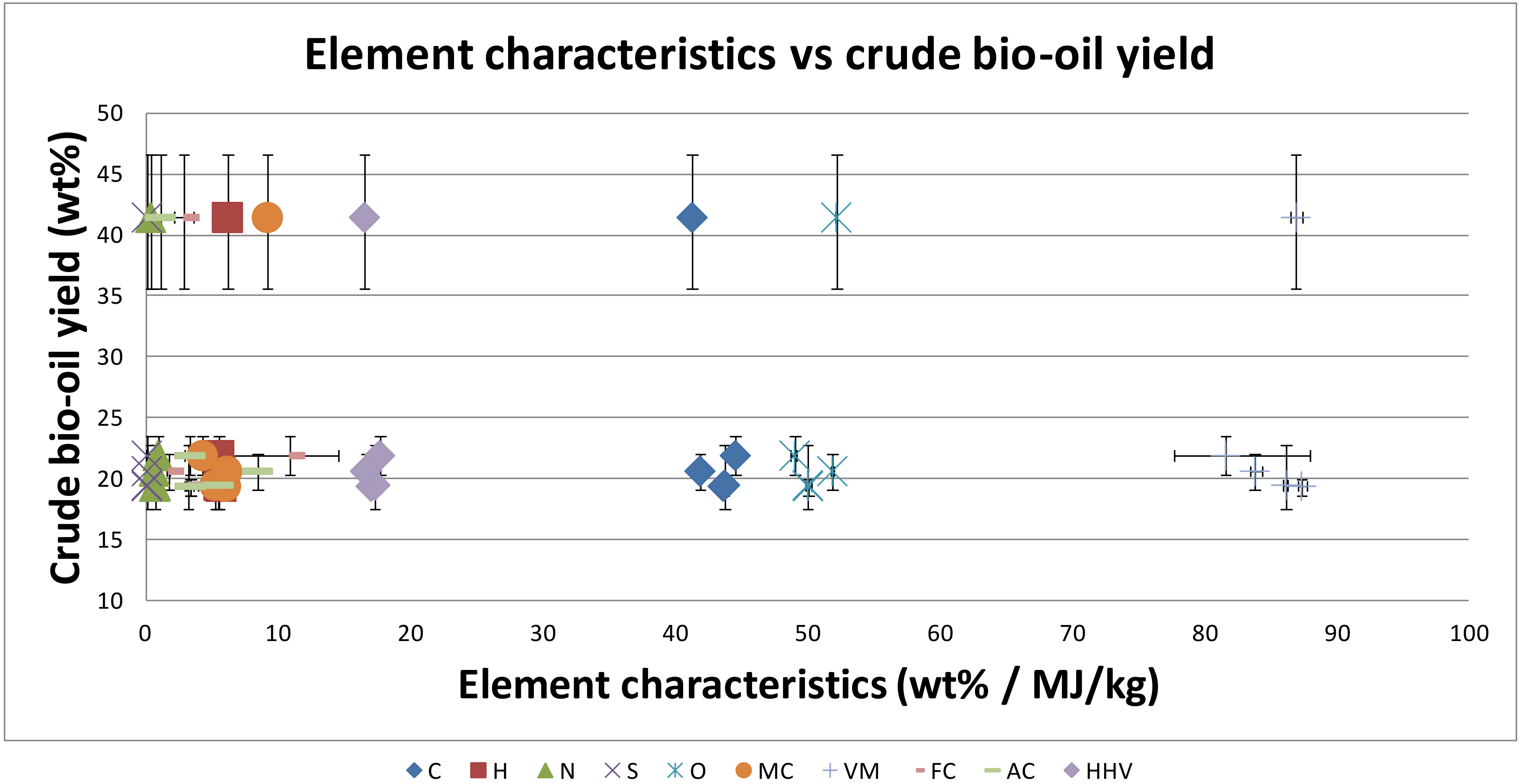
Biomass	C (wt%)	H (wt%)	N (wt%)	S (wt%)	O (wt%)	MC (wt%)	VM (wt%)	FC (wt%)	Ash (wt%)	HHV (MJ/kg)
1	44.5	5.5	0.9	0.1	49.0	4.3	81.6	10.8	3.3	17.6
2	43.6	5.7	0.6	0.0	50.0	6.0	87.3	3.3	3.3	17.0
3	41.3	6.1	0.4	0.1	52.2	9.2	86.9	2.9	1.1	16.5
4	43.7	5.5	0.7	0.1	50.0	5.2	86.2	3.2	5.4	17.3
5	41.9	5.6	0.6	0.1	51.9	6.1	83.8	1.7	8.4	16.6
Max	44.5	6.1	0.9	0.1	52.2	9.2	87.3	10.8	8.4	17.6
Min	41.3	5.5	0.4	0.0	49.0	4.3	81.6	1.7	1.1	16.5

Crude bio-oil yield analysis:

Table 5-8 tabulated the results of crude bio-oil yield from the pyrolysis process. In order to evaluate the relation between feedstock element characteristics and the process performances, the relation between each element characteristic and process outputs are plotted in graphs. Figures 5-6(a) shows the overall plot between feedstock element characteristics and crude bio-oil yield from the pyrolysis process; while Figure 5-6(b) highlight in detail individual relation between each element characteristics and bio-oil yield. Based on the graphs, the crude bio-oil yield obtained from the experiments are generally consistent in all different feedstocks, except for sample 3 which consist of 50 wt% NGS and 50 wt% sago. The crude bio-oil yield generated from sample 3 was significantly deviated from the rest of the feedstock types. It was found that more organic phase of crude bio-oil was produced when the sago biomass feedstock ratio increased to 50 wt%. This shows that introduction of 50 wt% sago as alternative biomass feedstock exceeded the process acceptance range and resulted major process output fluctuation in terms of crude bio-oil yield.

Table 5- 8: Bio-oil yield for pyrolysis experiment

Experiment Replication	Bio-oil yield (wt%)				
	1	**2**	**3**	**4**	**5**
1st	20.4	18.6	46.6	22.7	20.8
2nd	23.5	19.9	42.2	17.5	19.1
3rd	21.9	19.7	35.6	18.3	22.0
Avg	**21.9**	**19.4**	**41.5**	**19.5**	**20.6**



**refer to Figure 5-6(b) for detail relation between each element characteristics and bio-oil yield*

Figure 5- 6(a): Overall feedstock element characteristics vs crude bio-oil yield

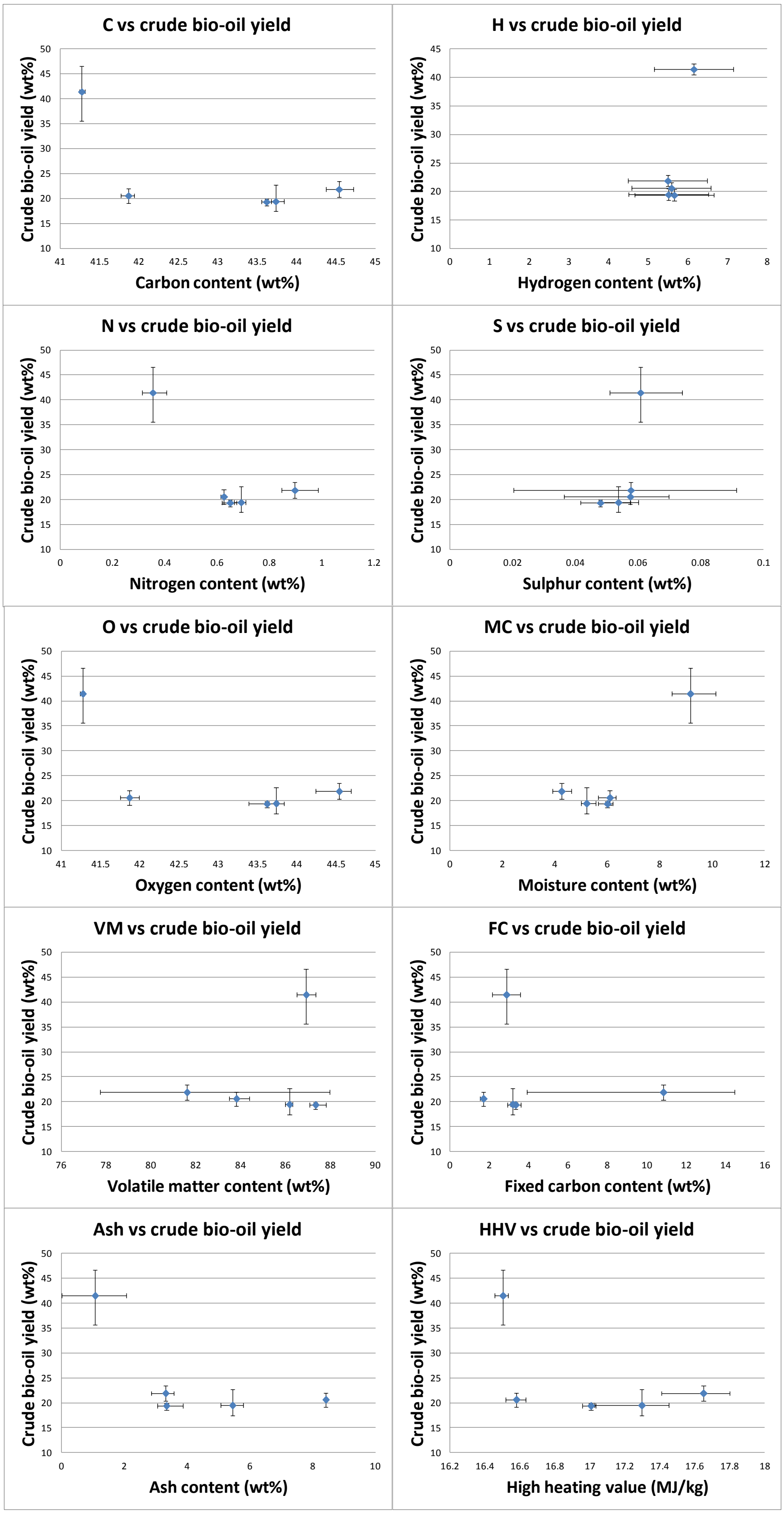
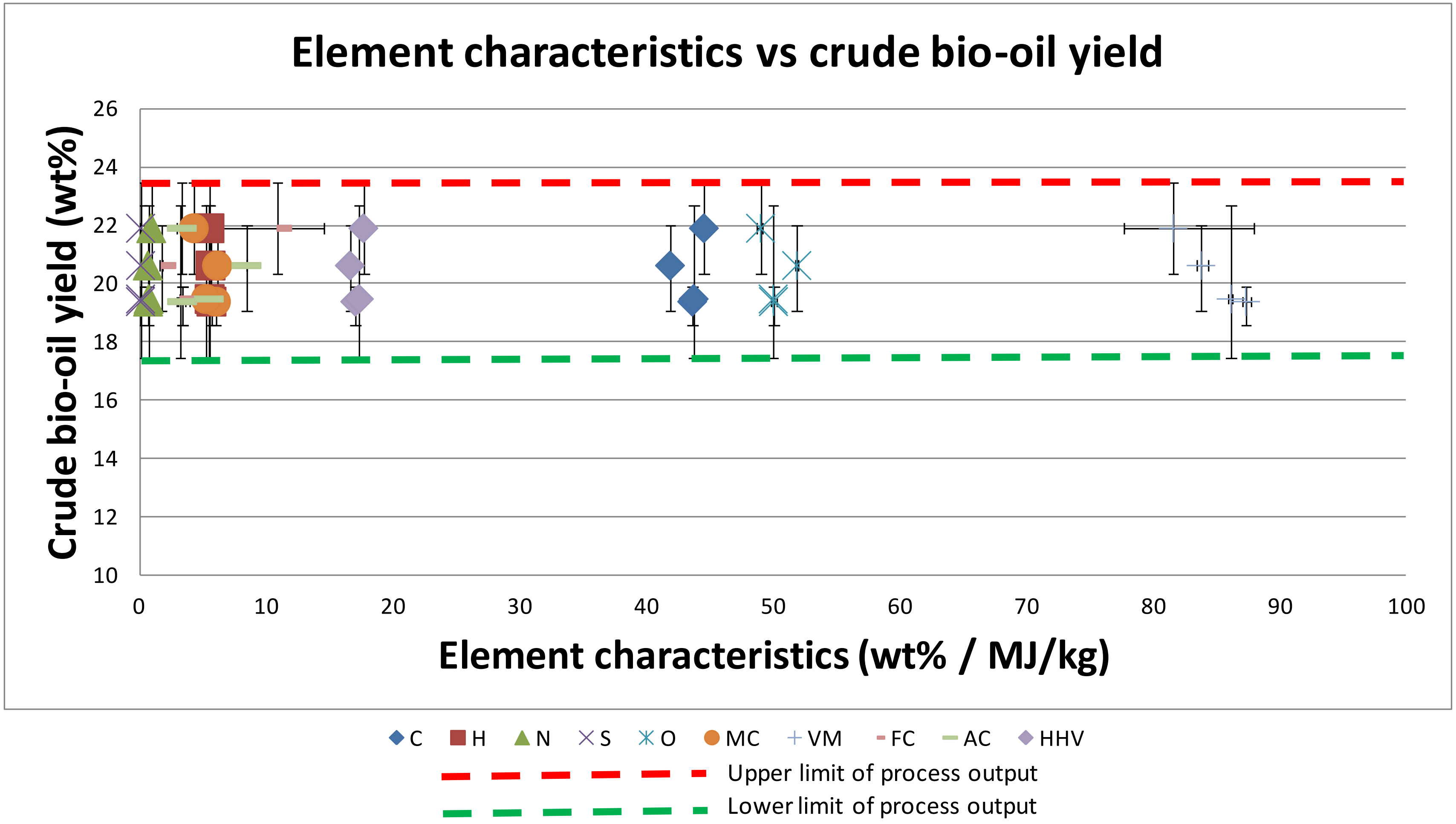


Figure 5- 6(b): Individual feedstock element characteristics vs crude bio-oil yield

Since the concept of element targeting is to ensure process consistency when integrating alternative biomasses, the technology element acceptance range has to reflect such that the process fluctuation is within an acceptable range. As discussed above, sample 3 (integrates up to approximately 50 wt% of sago biomass) in the experiment creates major deviation in bio-oil yield as compared to other feedstock, thus the analysis on the process acceptance range will be conducted with the exclusion of this data set. Figures 5-7(a) and 5-7(b) shows the same plot in Figures 5-6(a) and 5-6(b) without data obtained from sample 3. Based on the graphs, no significant trend of relation is observed between feedstock element characteristics and crude bio-oil yield. However, the result of crude bio-oil yield based on different feedstock is scattered in between 17.5 wt% to 23.5 wt%, with the overall average value of 20.35 wt%. This is considered as an acceptable fluctuation in process performance, which is in between approximately ±15%. Thus, based on the experiment results, the element acceptance range for this pyrolysis process experiment to achieve a bio-oil yield between 17.5 wt% to 23.5 wt% is constructed based on the maximum and minimum value of element characteristics of samples 1, 2, 4, and 5 as per Figure 5-8.



**refer to Figure 5-7(b) for detail relation between each element characteristics and bio-oil yield*

Figure 5- 7(a): Overall relation between feedstock element characteristics and crude bio-oil yield

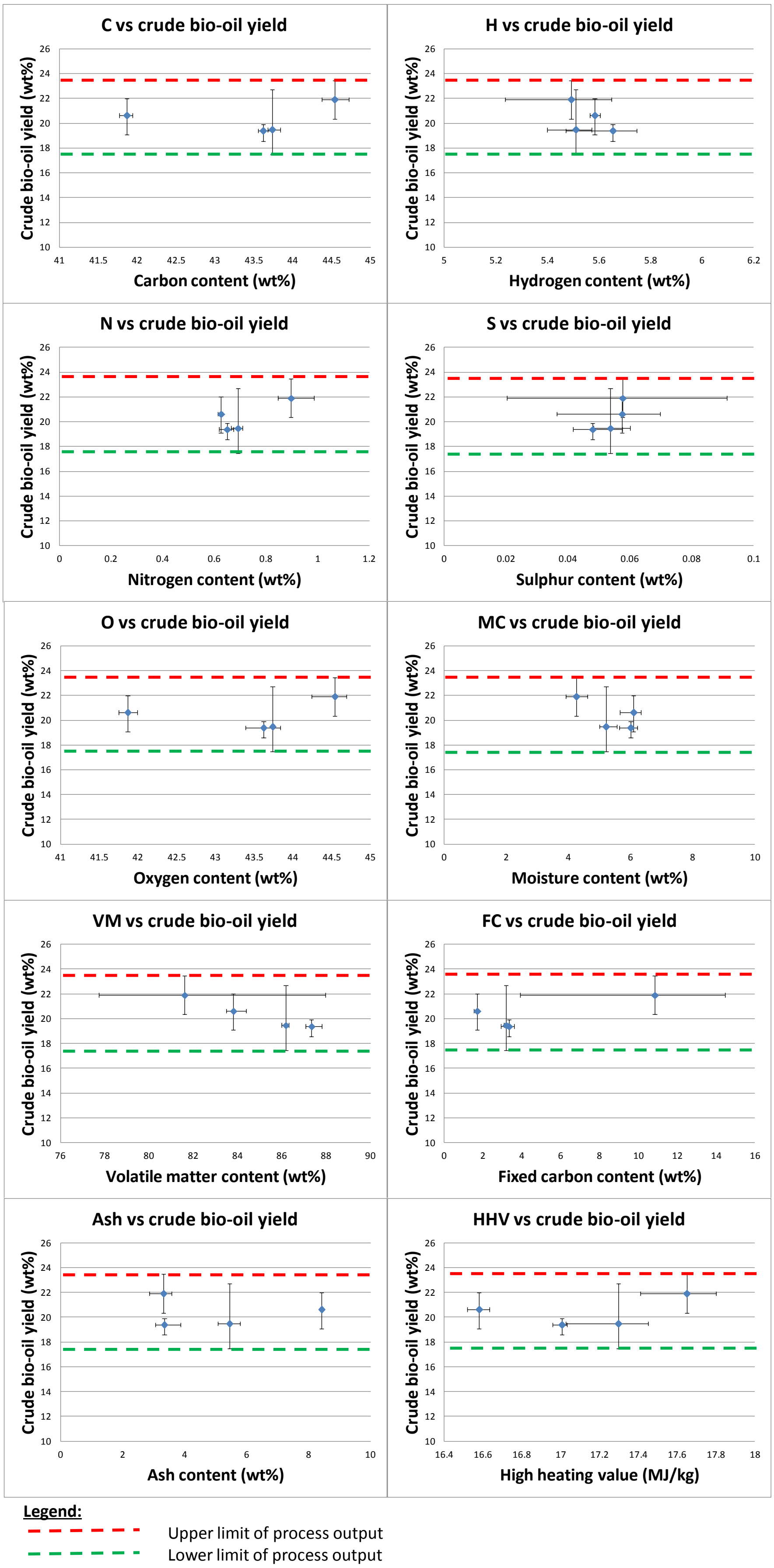
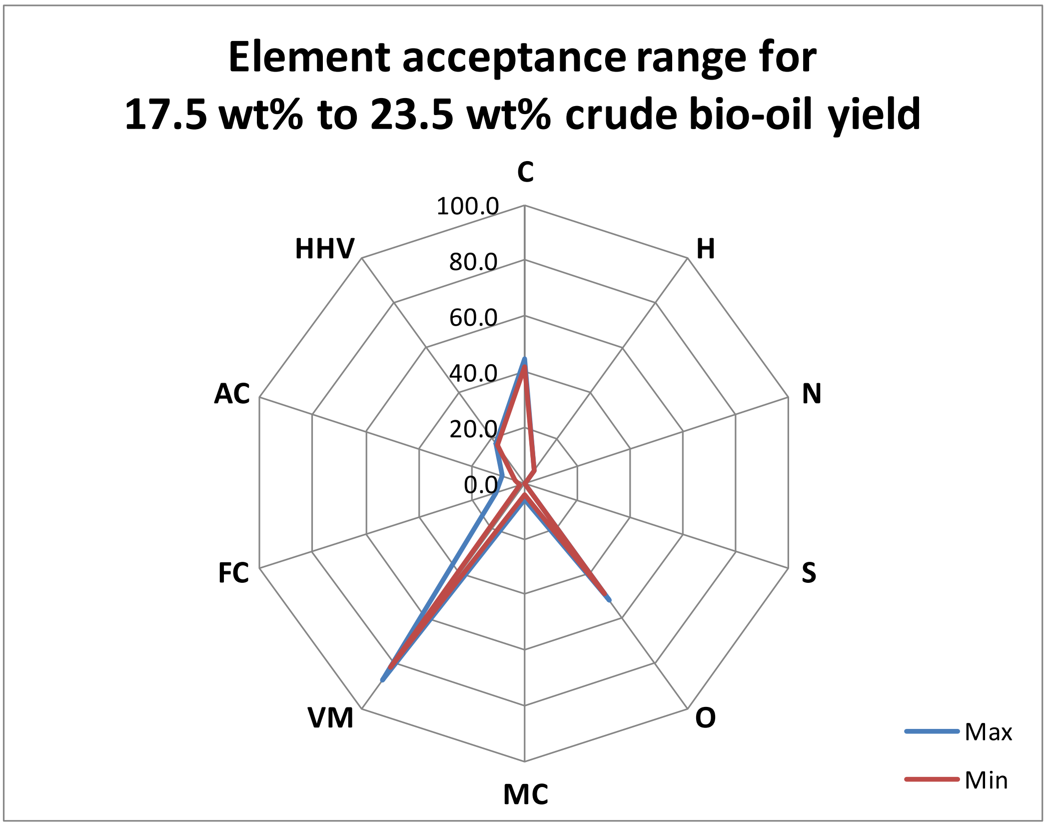


Figure 5- 7(b): Individual relation between feedstock element characteristics and crude bio-oil yield



	C	H	N	S	O	MC	VM	FC	AC	HHV
Max	44.54	5.65	0.90	0.06	51.87	6.10	87.33	10.85	8.42	17.65
Min	41.86	5.49	0.62	0.05	49.02	4.25	81.59	1.69	3.31	16.58

Figure 5- 8: Element acceptance range for targeted bio-oil yield

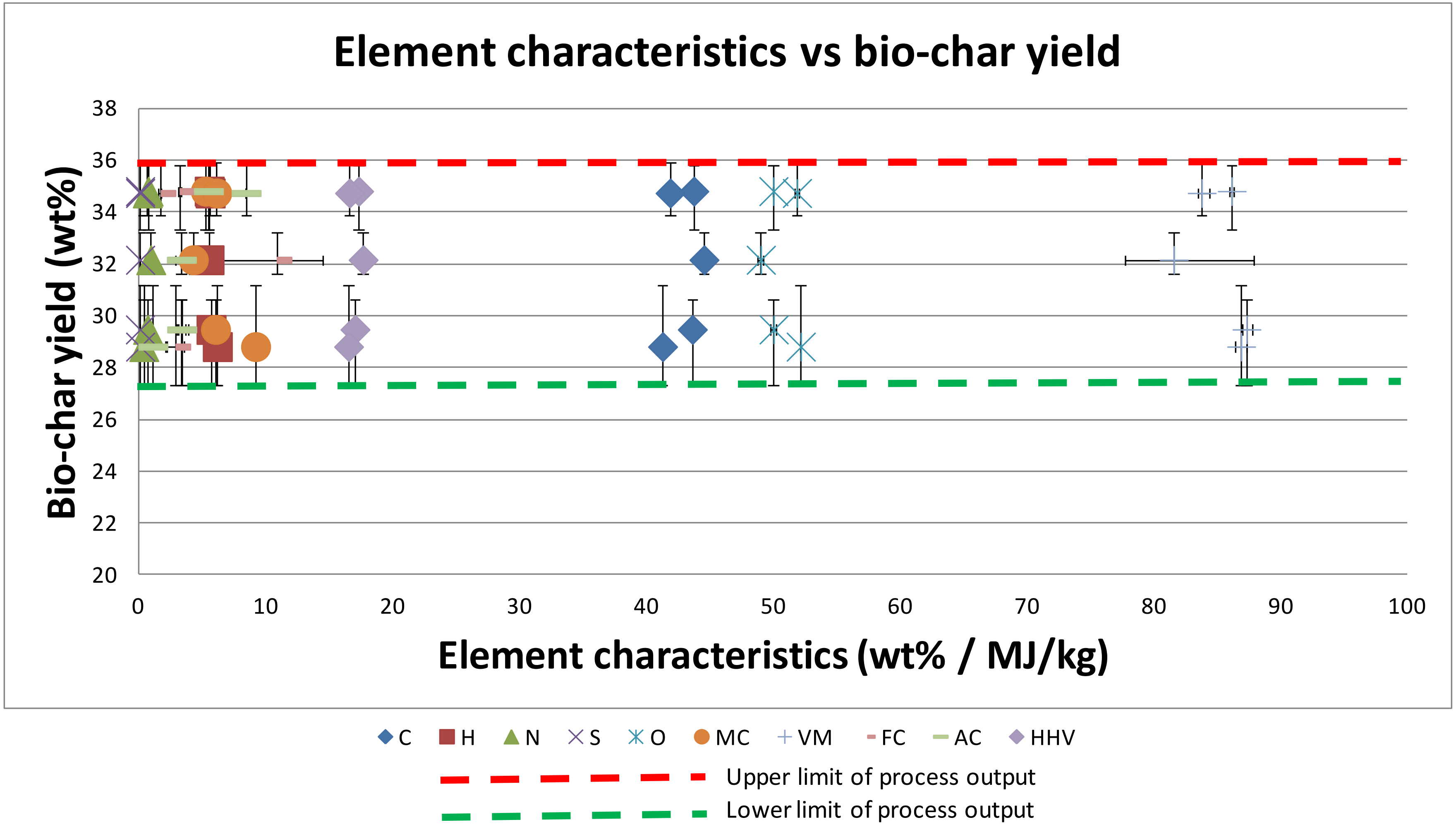
As discussed above, introduction of sago biomass up to 50 wt% (Sample 3) leads to considerable fluctuation in bio-oil yield while the remaining samples has less impact to the process output. In other words, out of the overall range of feedstock element characteristics that was evaluated in this study (as per Table 5-7), the proposed acceptable range in Figure 5-8 has lower maximum range/upper boundary in hydrogen content, sulphur content, oxygen content, moisture content; higher minimum range/lower boundary in carbon content, nitrogen content and higher heating value; and constant maximum/minimum range in volatile matters, fixed carbon content, and ash content. Nevertheless, the current experiment results are unable to determine the key element characteristic(s) that directly impact to the process fluctuation. Further analysis is required in future work to determine the key element with respect to the impact to process performance.

Bio-char yield analysis:

On the other hand, similar analysis was conducted to evaluate the relation between feedstock element characteristics and bio-char yield. Table 5-9 shows the bio-char yield from the experiment and Figures 5-9(a) and 5-9(b) presents the relation between feedstock properties and bio-char yield. No significant trend was observed in the majority of the plots, with an exception in graph ash content vs bio-char yield. When one of the data point (Sample 2) is excluded in the analysis, the result shows that increases of ash content in feedstock promotes higher bio-char yield as shown in Figure 5-10. This finding is comparable with Choi et al. (2014) in pyrolysis of seaweed. Nonetheless, the overall bio-char yield falls in between 27.3 wt% and 35.9 wt%, with an average of 32.0 wt%, which is considered to be an acceptable range for process fluctuation (within ±15%). Thus, the element acceptance range for the process to produce an average of 32.0 wt% of bio-char is proposed as per Figure 5-11.

Table 5- 9: Bio-char yield for pyrolysis experiment

Experiment Replication	**Char yield (wt%)**				
	1	**2**	**3**	**4**	**5**
1st	31.6	27.3	27.9	33.4	33.9
2nd	31.6	30.4	27.3	35.8	35.9
3rd	33.2	30.6	31.2	35.2	34.4
Avg	**32.2**	**29.5**	**28.8**	**34.8**	**34.7**



**refer to Figure 5-9(b) for detail relation between each element characteristics and bio-oil yield*

Figure 5- 9(a): Overall relation between feedstock element characteristics and bio-char yield

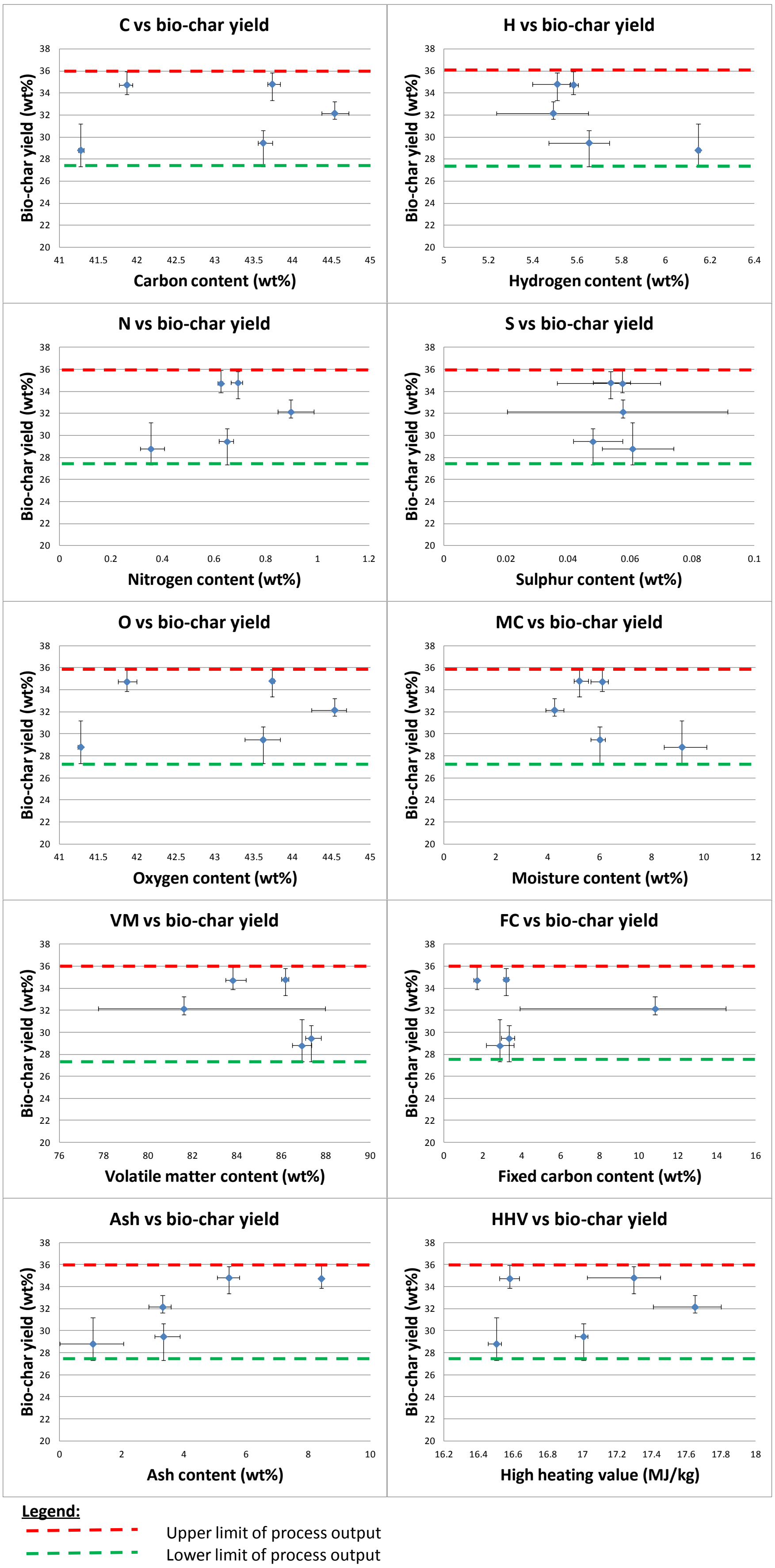


Figure 5- 9(b): Individual relation between feedstock element characteristics and bio-char yield

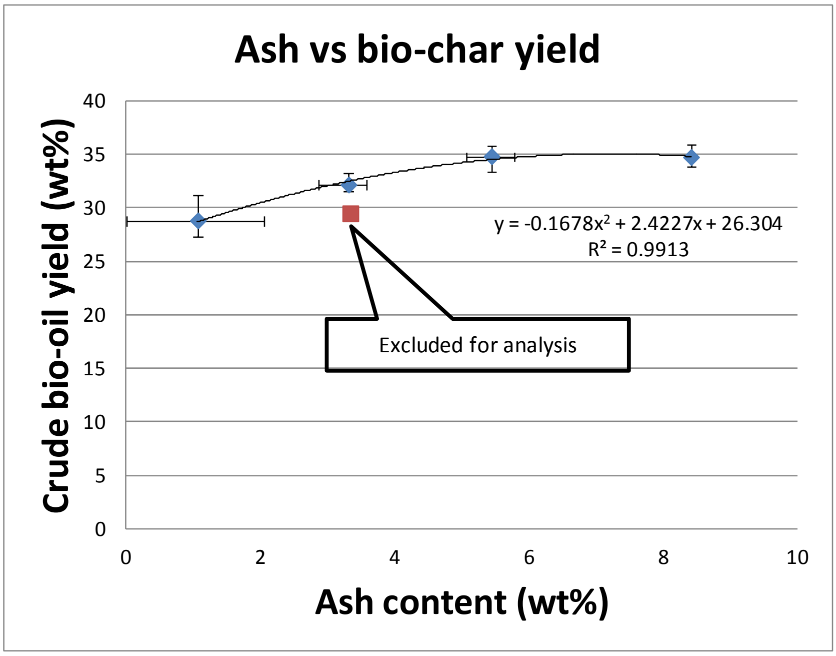
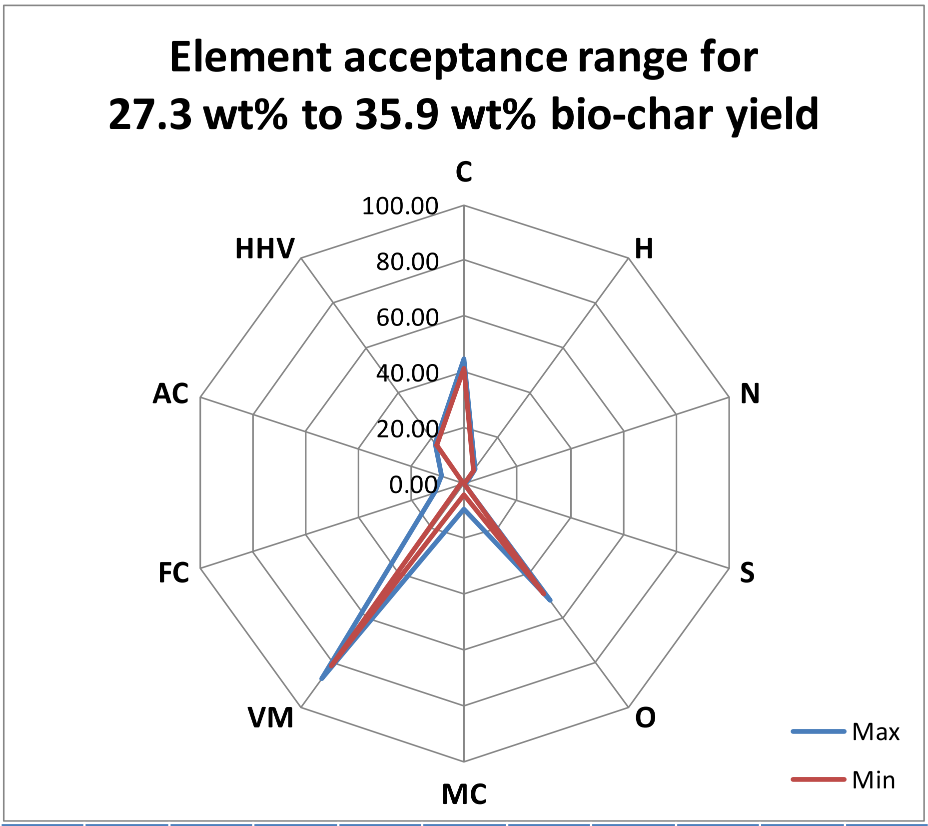


Figure 5- 10: Relation between feedstock ash content and bio-char yield



	C	H	N	S	O	MC	VM	FC	AC	HHV
Max	44.54	6.15	0.90	0.06	52.17	9.17	87.33	10.85	8.42	17.65
Min	41.27	5.49	0.35	0.05	49.02	4.25	81.59	1.69	1.07	16.50

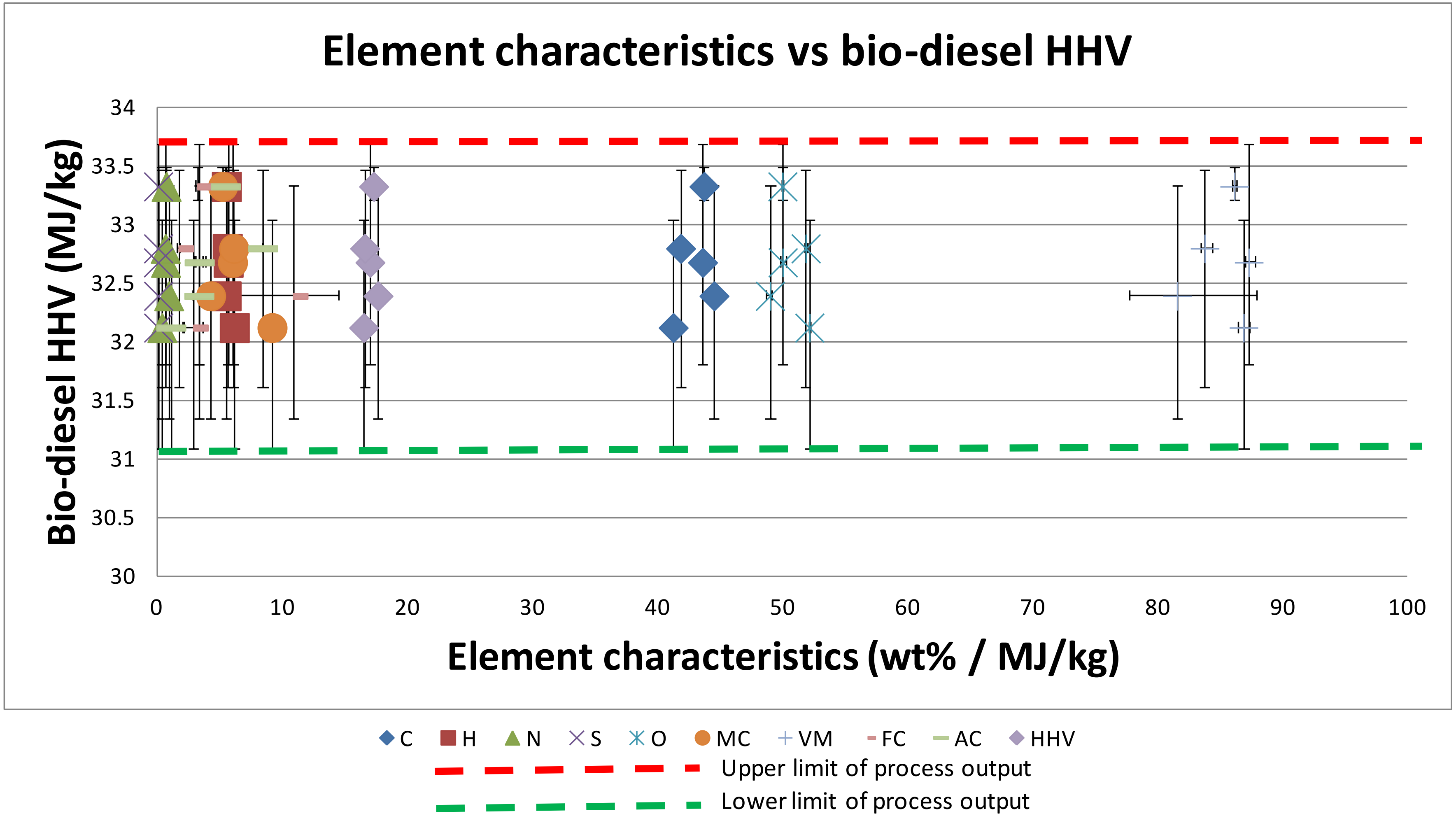
Figure 5- 11: Element acceptance range for targeted bio-char yield

Bio-diesel HHV analysis:

In terms of the impact of feedstock properties fluctuation to the bio-diesel HHV, Table 5-10 shows the result for each experiment run. Figures 5-12(a) and 5-12(b) plotted the relation between feedstock element characteristics and bio-diesel HHV for analysis. Based on the figure, the fluctuation of bio-diesel HHV is relatively smaller as compared to the previous analysis on crude bio-oil yield and bio-char yield. With the introduction of alternative feedstock of sago biomass and rice husk up to 50 wt% respectively, the produced bio-diesel from the pyrolysis process fluctuates from 31.1 MJ/kg to 33.7 MJ/kg, with an average value of 32.7 MJ/kg. The fluctuation in process performance is less than 5%, which is considered to be in acceptable range. As all the fluctuation of the feedstock element characteristics in the experiment are within the tolerance range, hence, the element acceptance range for the process to produce bio-diesel with HHV of approximately 32.7 MJ/kg is suggested as per Figure 5-13.

Table 5- 10: Bio-diesel HHV for pyrolysis experiment

Experiment Replication	Bio-diesel HHV (MJ/kg)				
	1	2	3	4	5
1st	24.1	27.3	25.6	29.3	29.5
2nd	27.1	30.6	22.9	30.1	24.8
3rd	29.6	24.5	28.3	29.4	29.9
Avg	**26.9**	**27.5**	**25.6**	**29.6**	**28.1**



**refer to Figure 5-12(b) for detail relation between each element characteristics and bio-oil yield*

Figure 5- 12(a): Overall relation between feedstock element characteristics and bio-diesel HHV

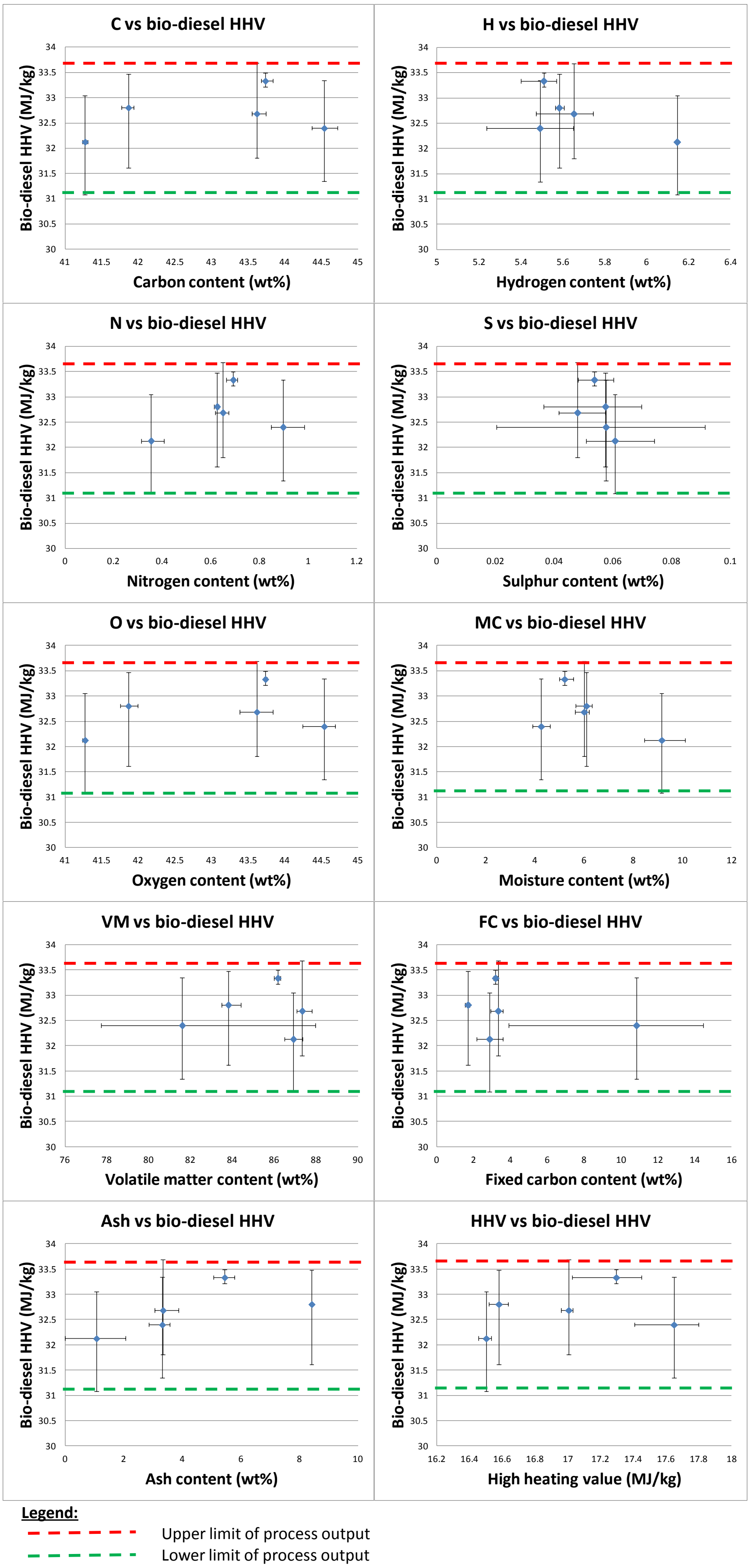
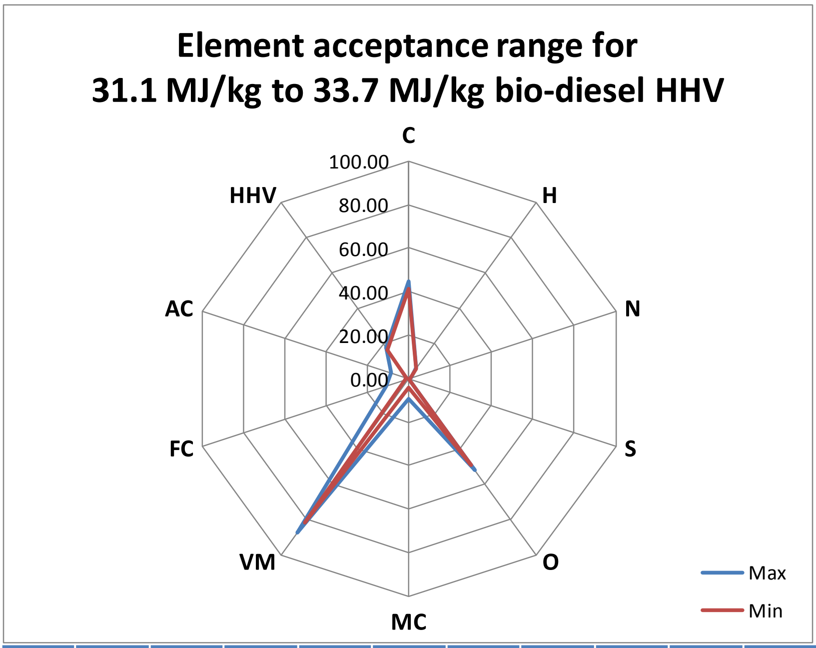


Figure 5- 13(b): Individual relation between feedstock element characteristics and bio-diesel HHV



	C	H	N	S	O	MC	VM	FC	AC	HHV
Max	44.54	6.15	0.90	0.06	52.17	9.17	87.33	10.85	8.42	17.65
Min	41.27	5.49	0.35	0.05	49.02	4.25	81.59	1.69	1.07	16.50

Figure 5- 14: Element acceptance range for targeted bio-diesel HHV

Based on the analysis, both element acceptance ranges for the target bio-char yield and bio-diesel HHV in Figures 5-11 and 5-13 respectively are found to be identical to each other. This is due to the fluctuation of feedstock element characteristics in this experiment (up to 50 wt% of sago biomass and rice husk respectively) has less impact to the process outputs. Inclusion of more biomass species or increasing mixing ratio of alternative biomasses will creates wider range in feedstock element characteristics to allow further analysis on the impact to respective process output and to evaluate greater feedstock fluctuation. Nevertheless, since the element acceptance range proposed in both Figures 5-11 and 5-13 are identical, this suggested that any biomass feedstock with element characteristics fall within this range will produce approximately 32.0 wt% of bio-char and bio-diesel of 32.7 MJ/kg.

On the other hand, the proposed element acceptance range for the pyrolysis process to produce an average of 20.35 wt% has smaller tolerance range as shown in Figure 5-8. As discussed earlier, introduction of 50 wt% of sago biomass into the system resulted in unacceptable/major bio-oil yield fluctuation. Thus in the case where all three process outputs (approximately 20.35 wt%, 32.0 wt% and 32.7 MJ/kg for bio-oil yield, bio-char yield, and bio-diesel HHV respectively) are taken into consideration, smaller feedstock tolerance range is the governing factor to ensure process consistency. In this case, Figure 5-8 will be the governing element acceptance range for the process as compared to Figures 5-11 and 5-13 to ensure all three process outputs are within the targeted value.

5.2.7 Limitation of element acceptance range via laboratory experiment

Previous section has demonstrated the relation between feedstock element characteristics and their impact to process outputs fluctuation. The information can be utilised in feedstock selection to allow integration of alternative biomasses into the process. Optimum biomass mixing ratio can also be determine by using mathematical model, which will be discussed in next chapter. No doubt that experimental approach is a more promising approach to evaluate the feedstock tolerances as compared to literature review as suggested in Chapter 4, the evaluation of element acceptance range for biomass process technology via laboratory experiment still has its limitation. Experimental work often required more time and funding for evaluation and limitation in sample size such as availability of biomass species will limit the coverage of the study. For instance, the range of feedstock properties studied in this research is subjected to the range in Table 5-7 only. Diversify biomass species as feedstock for experiment enables the analysis to cover wider feedstock element acceptance range.

Study wider range of feedstock element characteristics can further enhance the analysis of the impact of each biomass properties to the process output which are essential to determine the key element and construction of general co-relation for pyrolysis process. For example, researches show that different mineral interacts differently during thermochemical conversion (Ellis et al., 2015). Mineral within different biomass has the potential to react with each other and interferes the overall process reaction. Specific mineral can also be used as catalyst for pyrolysis to control and achieve particular bio-oil quality. However in this research, mineral content is not considered as part of the feedstock properties. Thus, analysis and comparison of the potential key element is unable to be conducted. This suggested that the element targeting approach can be further improved by considering feedstock mineral content as part of the key elements that can impact to process. Nevertheless, catalytic reaction may be able to minimise the impact of mineral content, due to the controlled reaction mechanism. This will enables proximate estimation of bio-oil compound in the process output without biomass mineral constraints. Other feedstock properties to be considered in future works are cellulose, hemicellulose and lignin content.

On the other hand, the proposed element acceptance range in this study is only limited to the proposed experiment set up and operating conditions which is also parallel with the result obtained in Chapter 4. Impact of the relation between feedstock and process performance due to process modification is not considered in this study. Further verification on the impact of respective process modification (such as feedstock size, reactor size, cooling time and temperature, and pyrolysis temperature) to the process performance will enable process optimisation based on feedstock properties. Nonetheless, the current study has provided a good platform for alternative feedstock integration without process modification via element characteristic, which is one of the main advantages for existing process plant to avoid investment into process modification or new technologies.

5.3 Conclusions

In this chapter, two set of experiments were conducted to investigate the prediction of biomass mixture element characteristic and to investigate the relationship between biomass feedstock and pyrolysis technology performance. Total of three biomass species, including Napier grass stem, rice husk and sago biomass, and variation of their mixtures were used as biomass feedstock for process to create a variety of feedstock properties for investigation. The first section of the chapter has shown that biomass mixture properties can be estimated based on the mass ratio, which supported the assumption in Chapter 3. This enables the calculation of biomass feedstock ratio based on the element acceptance range of respective process technologies to ensure that the mixture properties are within the process acceptance range.

The next section of the chapter has evaluated the concept of element acceptance range for biomass process technologies proposed in Chapter 3. The result has shown that the element acceptance range can be constructed according to the process performance fluctuation from the experiment, where the process performance can be predicted as long as the biomass feedstock element characteristics are within the element acceptance range. Both the result obtained from this chapter based on pyrolysis experiment and literature review on gasification technology from Chapter 4 have supported the concept of element targeting where selection of feedstock can based on element characteristics instead of biomass species to promote utilisation of alternative biomasses.

This chapter has provides a systematic verification for the novel concept of element targeting approach. Nevertheless, the selection of feedstock based on element characteristics is a complicated process due to various variables to be considered. Mathematical optimisation model integrated with the element targeting approach will be proposed in next chapter to improve the biomass selection in regional biomass supply chain network management via consideration of alternative biomasses and transform concept of element targeting approach into useful industrial application as decision making tool in biomass supply chain.

Chapter 6:
BIOMASS SUPPLY CHAIN OPTIMISATION VIA ELEMENT TARGETING APPROACH

A state-of-the-art element targeting approach is introduced in this thesis to enhance the feedstock flexibility for biomass technologies by integrating all biomass species, including underutilised biomass into the system for optimum supply chain management. Applicability of this novel approach was verified in previous two chapters. However, due to the limitation of funding and research time, the verifications were confined to two biomass technologies, i.e. gasification and pyrolysis. Nevertheless, both investigations show good relation between biomass feedstock element characteristic with technology performance. Thus, it is suggested that element targeting approach is generally applicable to majority of the biomass technologies provided with some logical assumptions or extended study on element acceptance range of the technology.

Current chapter discussed the application of element targeting approach in biomass supply chain management and optimisation. It is the ultimate goal of the research to enhance the distribution network and logistic of biomass industry, in order to improve the implementation of the sustainable resources. Several demonstration case studies are conducted to illustrate the advantages of element targeting as compared to the existing supply chain optimisation model.

6.1 Problem statement and objectives

As discussed in Chapter 1, one of the main problems in current biomass industry is the ignorance of potential value in biomass, especially on those non-main stream biomasses as alternative feedstock for process technologies due to the lack of technology development which leads to underutilisation of biomass. This thesis has introduced and verified a novel integration approach to consider alternative biomasses in existing technologies in previous chapters. In this chapter, the main objective is to integrate the proposed element targeting approach into mathematical biomass supply chain optimisation model. Two models are introduced, namely Demand-Resources Value Targeting (DRVT) and Biomass Element Cycle Analysis (BECA).

6.2 Demand-Resources Value Targeting Approach

As discussed above, this chapter emphasises on the application of element targeting approach in biomass supply chain optimisation model. The first demonstration case study looked into the comparison between conventional biomass supply chain model and a newly proposed element targeting approach. *Demand-Resources Value Targeting (DRVT)* approach is introduced as a biomass supply chain optimisation model integrated with element targeting approach. DRVT is a novel biomass supply chain mathematical model to optimise the network by consideration of alternative biomass species available within the system. The model utilises element targeting approach as the feedstock selection platform which determine the feasibility of respective alternative biomass to be utilised in the pre-existed process plant. Depending on the technology feedstock element characteristics tolerances, the model will also determines the optimum feedstock ratio to ensure consistency of process performance. Integration of element targeting into biomass supply chain optimisation model enables the consideration of alternative feedstock including underutilised biomass which potentially at lower material cost and logistic cost thus improves the overall system performance and sustainability.

6.2.1 Methodology for Demand-Resources Value Targeting approach

The following subsections are the proposed methodology to implement the DRVT approach into existing biomass industry and supply chain network management.

6.2.1.1 Exploitation of regional biomass system

Data collection based on regional biomass system, including available resources, existing process plants and technologies, market demands and logistic and location data (distance and cost of transportation). Each regional biomass system has a distinguish pattern, thus data collection is essential to optimise the biomass supply chain network.

6.2.1.2 Identify biomass element characteristics

The main advantage of DRVT approach is to enable the supply chain model to select biomasses based on their properties. Thus, the next step is to determine the element characteristics of each biomass based on literature or laboratory analysis. The element to be considered are generally consist of (but not limited to) moisture content (MC), fixed carbon (FC), ash content (Ash), volatile matter (VM), heat value (HV), carbon content (C), hydrogen content (H), nitrogen content (N), oxygen content (O), sulphur content (S), cellulose content (Cell), hemicellulose content (Hcel), and lignin content (Lig). Element to be considered in the study is based on available data, as well as the element acceptance range of respective technology. If key elements are not predefined, the model should consider as many element characteristics as possible to minimise feedstock fluctuation.

6.2.1.3 Identify technology element acceptance range

Element acceptance range of each technology can be constructed based on the suggested approach in Chapter 3, which is based on a well established relation, or original biomass feedstock properties and natural fluctuation of biomass properties. This information is the key factors as the feedstock selection platform in the model.

6.2.1.4 Integration into the Demand-Resources Value Targeting model

Upon data collection, the complex supply chain network can be solved using a mathematical model. The following shows the mathematical model for DRVT approach.

<u>Element constraint:</u>

This section of the model formulation addresses the element targeting approach. A series of equation ensure the overall biomass feedstock element characteristics are within the element acceptance range for respective technologies. Equation 6-1 indicates the calculation of total biomass element, ***e*** received in each process plant, ***j*** for each biomass, ***m***, $\mathrm{EleRecT}(m, e, j)$ based on biomass, ***m*** received at process plant, ***j*** $\mathrm{MatRecT}(m, j)$ and biomass element characteristics, $\mathrm{Element}(m, e)$.

$$\mathrm{MatRecT}(m, j) \times \mathrm{Element}(m, e) = \mathrm{EleRecT}(m, e, j) \quad \forall\, m, e, j \tag{6-1}$$

Equation 6-2 indicates total biomass received at process plant, ***j***, $\mathrm{TMatRec}(j)$ by combining each biomass ***m***, at each process plant ***j***, $\sum_{m=1}^{M} \mathrm{MatRecT}(m, j)$.

$$\sum_{m=1}^{M} \mathrm{MatRecT}(m, j) = \mathrm{TMatRecT}(j) \quad \forall j \tag{6-2}$$

Equation 6-3 indicates total biomass element characteristic, ***e*** received in process plant, ***j***, $\sum_{m=1}^{M} \mathrm{EleRecT}(m, e, j)$ should be less than the upper limit of element acceptance range, ***e*** at respective process plant, ***j***, $\mathrm{E\_upper}(e, j)$ multiply with total biomass received at process plant, ***j***, $\mathrm{TMatRec}(j)$.

$$\sum_{m=1}^{M} \mathrm{EleRecT}(m, e, j) \le \mathrm{E\_upper}(e, j) \times \mathrm{TMatRecT}(j) \quad \forall\, e, j \tag{6-3}$$

Similarly, Equation 6-4 indicates total biomass element characteristic, ***e*** received in process plant, ***j***, $\sum_{m=1}^{M} \mathrm{EleRecT}(m, e, j)$ should be more than the lower limit of element acceptance range, ***e*** at respective process plant, ***j***, $\mathrm{E\_lower}(e, j)$ multiply with total biomass received at process plant, ***j***, $\mathrm{TMatRec}(j)$.

$$\sum_{m=1}^{M} \mathrm{EleRecT}(m, e, j) \ge \mathrm{E\_lower}(e, j) \times \mathrm{TMatRecT}(j) \quad \forall\, e, j \tag{6-4}$$

<u>Mass constraint:</u>

This section governs the overall material balance of system, in other word the mass balance of each point of integration. Equation 6-5 restricts total amount of each biomass, ***m*** sent from resource location, ***i***, $\sum_{j=1}^{J} RtoT(i, m, j)$ cannot more than total biomass available at each resource location, ***i***, $\mathrm{Resource}(i, m)$.

$$\sum_{j=1}^{J} RtoT(i, m, j) \le \mathrm{Resource}(i, m) \quad \forall\, i, m \tag{6-5}$$

Equation 6-6 stated that total of each biomass, ***m*** received at each process plant, ***j***, $\mathrm{MatRecT}(m,j)$ is the same amount of biomass, ***m*** delivered from resource location***, i*** to process plant, ***j***, $\sum_{i=1}^{I} RtoT(i,m,j)$.

$$\sum_{i=1}^{I} RtoT(i,m,j) = \mathrm{MatRecT}(m,j) \quad \forall\, m,j \tag{6-6}$$

Equation 6-7 indicates $\mathrm{MatGenT}(m,jp)$ is the total product, ***m***, generated at each process plant, ***j***. In Chapter 3, two approaches are introduced to construct element acceptance range: i) based on well-developed relation between feedstock properties and process output, and ii) based on original biomass feedstock. The first term in Equation 6-7 is to calculate product generated, m at process plant, ***jp*** where the yield is determined based on specific biomass element, ***e***. $\sum_{\mathrm{m}=1}^{\mathrm{M}} \mathrm{EleRecT}(m,"e=e","j=j")$ indicates the total specific element, ***e*** received at a specific process plant, ***j*** multiply with the conversion factor based on specific element, ***e*** for respective process plant, ***j***, $ele\_\mathrm{yield}("\mathrm{j{=}j}",m,jp)$. The second term is the calculation of product generated, m, at process plant, j where the yield is determind based on the total amount of biomass, m received at the respective process plant, $\mathrm{TMatRecT}("j=j")$ multiply with the process conversion of that particular process plant, $mass\_\mathrm{yield}("j{=}j",m,jp)$. Equation 6-8 constraints that total product generated, ***m*** in each process plant output, ***jp***, $\mathrm{MatGenT}(m,jp)$ should be more or equals to total product, ***m*** sent to market demand, ***k***, $\sum_{k=1}^{K} TtoD(jp,m,k)$.

$$\begin{aligned}\sum_{j=1}^{J}\left[\sum_{\mathrm{m}=1}^{\mathrm{M}} \mathrm{EleRecT}(m,"e=e","j=j") \times ele\_\mathrm{yield}("j{=}j",m,jp)\right] \\ + \sum_{j=1}^{J}\left[\mathrm{TMatRecT}("j=j") \times mass\_\mathrm{yield}("j{=}j",m,jp)\right] \\ = \mathrm{MatGenT}(m,jp) \qquad \forall\, m,jp\end{aligned} \tag{6-7}$$

$$\sum_{k=1}^{K} TtoD(jp,m,k) \le \mathrm{MatGenT}(m,jp) \quad \forall\, m,jp \tag{6-8}$$

Equation 6-9 stated total production of each process plant, $\sum_{j=1}^{J} TtoD(jp,m,k)$ has to fulfil minimum local market demand, $\mathrm{Lower\_Demand}(m,k)$. Excess production will be exported to other region with the limitation of $\mathrm{Upper\_Demand}(m,k)$. In case of no constraint for exportation, an immense value of material, ***m*** is assigned in the export location, ***k*** in $\mathrm{Upper\_Demand}(m,k)$.

$$\text{Lower\_Demand}(m,k) \leq \sum_{j=1}^{J} TtoD(jp,m,k) \leq \text{Upper\_Demand}(m,k) \quad \forall\, m,k \tag{6-9}$$

Cost calculation:

The overall transportation cost is calculated based on the weight of the material and the distance of transportation depending on the transportation mode. Equation 6-10 indicates the transportation cost of sending biomass, ***m*** from resources location, ***i*** to process plant, ***j***, $\text{Cost\_RtoT}(i,j)$ based on total biomass, ***m*** from resources, ***i*** to process plant, j, $\sum_{m=1}^{M} RtoT(i,m,j)$, distance between resource, ***i*** and process plant, ***j*** based on transportation mode, ***r*** $\text{Distance\_RtoT}(i,j,r)$ and the flat rate transportation cost of the particular transportation mode, $\text{Transcost}(r)$, in $ /t/km.

$$\sum_{m=1}^{M} RtoT(i,m,j) \times \sum_{r=1}^{R} [\text{Distance\_RtoT}(i,j,r) \times \text{Transcost}(r)] = \text{Cost\_RtoT}(i,j) \quad \forall\, i,j \tag{6-10}$$

Similarly, Equation 6-11 indicates transportation cost of sending product, ***m*** from process plant output, ***jp*** to market demand, ***k***, $\text{Cost\_TtoD}(jp,k)$ based on total biomass, ***m*** from process plant output, ***jp*** to demand, ***k***, $\sum_{m=1}^{M} TtoD(jp,m,k)$, distance between process plant, ***jp*** and demand, ***d***, $\text{Distance\_TtoD}(jp,k,r)$ based on the transportation mode, ***r*** and flat rate transportation cost of the particular transportation mode, $\text{Transcost}(r)$, in $ /t/km. In reality, transportation cost is subject to mode of transportation (size), transportation route, road condition, and material properties (bulk density). However, these are not the main objective of this work and many research has conducted (as discussed in Chapter 2), thus a flat rate for transportation cost calculation based on specific mode of transportation (such as truck or train) ($ /t/km) is considered to simplify the model.

$$\sum_{m=1}^{M} TtoD(jp,m,k) \times \sum_{r=1}^{R} [\text{Distance\_TtoD}(jp,k,r) \times \text{Transcost}(r)] \\ = \text{Cost\_TtoD}(jp,k) \qquad \forall\, jp,k \tag{6-11}$$

Total transportation cost of the system, TTranscost is represented in Equation 6-12, which is the summation of all $\text{Cost\_RtoT}(i,j)$, and $\text{Cost\_TtoD}(jp,k)$.

$$\sum_{\mathrm{i,j=1}}^{\mathrm{I,J}}[\mathrm{Cost\_RtoT}(i,j)] + \sum_{\mathrm{jp,k=1}}^{\mathrm{JP,K}}[\mathrm{Cost\_TtoD}(jp,k)] = \mathrm{TTranscost} \tag{6-12}$$

Equation 6-13 indicates the profit by calculating the difference between profit earned per unit of product, ***m*** sold to demand, ***k***, and cost per unit biomass, ***m*** obtained from resources, ***i***. Noted that $\mathrm{Value}(m)$ is refer to the price of raw biomass (excluding transporation cost) and gross profit of product (excluding transporation cost and raw material cost).

$$\mathrm{Profit} = \sum_{m=1}^{M}\left[\left(\sum_{jp,k=1}^{JP,K} TtoD(jp,m,k)\right) \times \mathrm{Value}(m)\right] - \sum_{m=1}^{M}\left[\left(\sum_{i,j=1}^{I,J} RtoT(i,m,j)\right) \times \mathrm{Value}(m)\right] \tag{6-13}$$

<u>Objective function:</u>

Finally, Equation 6-14 shows the overall total profit of the system, $\mathrm{Totalprofit}$ after consideration of total transportation cost, $\mathrm{TTranscost}$.

Maximising Totalprofit:

$$\mathrm{Totalprofit} = \mathrm{Profit} - \mathrm{TTranscost} \tag{6-14}$$

6.2.2 Demonstration case study for Demand-Resources Value Targeting approach

The following demonstrates a case study of DRVT approach based on a demonstration of regional biomass system. The first step is to collect important information as discussed above in DRVT methodology. Figure 6-1 shows a Cartesian coordinate mapping for the proposed case study. Each unit of coordinate represent 100 km in distance. Assuming 4 resources points and 4 demand points are identified, Tables 6-1(a) and 6-1(b) summarise the overall resources availability and market demand in this region, as well as the market prices respectively. Noted that the prices stated is referring to the material cost for resources; or gross profit of selling a unit of demand to the market for demands (excluding raw biomass and transportation cost). The conversion from RM to $ is based on a constant rate of 4 to 1. These information will be utilised as the input data for the regional biomass system to optimise the overall supply chain network.

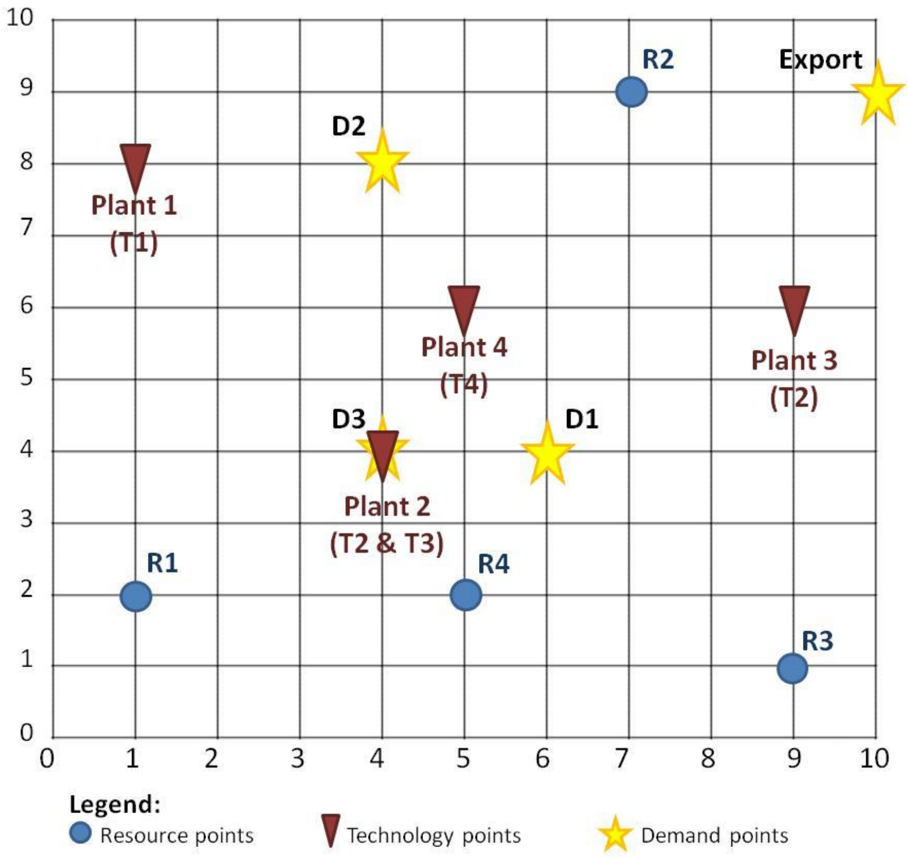


Figure 6- 1: Cartesian coordinate mapping for case study

Table 6- 1(a): Information on resources at each location

Location	Biomass	Availability (t/day)	Price (RM/unit)	Price ($/unit)
R1	Palm shell	2500	120	30.00
	Oil palm fronds	1500	110	27.50
	Palm oil EFB	2000	105	26.25
	Palm kernel trunk	800	65	16.25
R2	Palm shell	1750	120	30.00
	Oil palm fronds	2300	110	27.50
	Palm oil EFB	2100	105	26.25
	Palm Mesocarp Fibre	750	75	18.75
R3	Soft wood	1500	50	12.50
R4	Hard wood	1750	85	21.25

Table 6-1(b): Information on demands at each location

Location	Product	Market Demand (t/day)	Price (RM/unit)	Price ($/unit)
D1	Bio-oil	1600	300	75.00
	Bio-ethanol	1550	450	112.50
D2	Syngas	860 (N/m^3)	325	81.25
D3	Syngas	350 (N/m^3)	325	81.25
	Power	1200 (MJ)	260	65.00
Export	Bio-oil	Unlimited	300	75.00
	Syngas	Unlimited	325	81.25
	Bio-ethanol	Unlimited	450	112.50

On the other hand, Table 6-2 tabulates general information on existing technologies within the system. Information of the technologies was obtained from respective literatures with the assumption that the process performances are the same in industrial scale as compared to the reported laboratory scale. Since the focus of the research is on technology feedstock selection, only one mode of transportation (truck) (RM 0.5 /t/km)($ 0.125 /t/km) is considered in this case study.

Table 6- 2: Information on technologies present in the region

No.	Technology	Feedstock	Conversion Yield	Reference
T1	Bio-oil production via pyrolysis	Palm shell	46.1 wt% of feedstock	Abnisa et al., (2011)
T2	Syngas production via gasification	Oil palm fronds	1.94 Nm^3 per kg of feedstock	Guangul et al., (2012)
T3	Power generation plant	Oil palm fronds	10.30 MJ per kg of feedstock	Guangul et al., (2012)
T4	Production of bio-ethanol via fermentation	Palm oil EFB	24.16 wt% of feedstock	Sudiyani et al., (2013)

The next step is to compile element characteristic of the respective biomasses available within the system. Table 6-3 summaries the biomass properties based on literature. As discussed in Chapter 4 and Chapter 5, element acceptance range of biomass processes can be different from each process technology, depending on the equipment setup and operating conditions. In this case study, properties of the feedstock biomass evaluated in the literature for all four technologies were subjected to cellulose content (Cel), hemicellulose content (Hcel), lignin content (Lig), extractives (Ext), ash content (Ash), and moisture content (MC). Although the case study can include more element characteristics in the feedstock selection platform based on the reported property value from other literature, however the information might not be accurate as same biomass species can have high properties fluctuation depending on the region, harvesting method, logistic, and weather. Thus, exploration of element acceptance range for respective technologies is conducted based on the reported biomass feedstock species and element characteristics only, where all 6 element characteristics are assumed to be the key elements in the feedstock selection.

According to the respective literature, all four biomass technologies were developed based on single original biomass feedstock species. In other word, impact of alternative biomass feedstock into the same technology is not evaluated. In addition, no clear relation between each element characteristics and the process performance was reported. Thus the construction of element acceptance based on original feedstock properties (as discussed in Section 3.4.2.) is the better option. When translate to the modelling equation to determine the product generation (Equation 6-7), $ele\_\text{yield}(\text{"j=j"}, m, jp)$ is set to be zero as production can not be determined by element received at respective process plant; while $mass\_\text{yield}(\text{"j=j"}, m, jp)$ for T1 to T4 is set to be at 0.461 kg of bio-oil per kg feedstock, 1.94 Nm^3 of syngas per kg feedstock, 10.30 MJ per kg feedstock, and 0.2416 kg of bio-ethanol per kg feedstock respectively. Figure 6-2 shows the element acceptance range for respective technology in this case study, with the assumption that each technology can tolerance ±5% fluctuation in each feedstock element characteristics considered in this case study. This is considered as an acceptable assumption based on the general biomass properties fluctuation in the resources due to harvesting, logistics, weather, and season. Consideration of more element characteristics will further constraint the feedstock properties fluctuation and ensure better consistency to control the process outputs.

Table 6- 3: Information on technologies present in the region

Biomass	Biomass Element Characteristics (wt%)						
	Cel	Hcel	Lig	Ext	Ash	MC	Ref.
Palm shell	27.7	21.6	44.0	2.0*	2.1	11.0	Abnisa et al., (2011)
Oil palm fronds	30.4	40.4	21.7	2.7	1.30	16.0	Kelly-Yong et al., (2007), Guangul et al., (2012)
Palm oil EFB	37.3	14.6	31.7	1.3	6.7	10.0	Sudiyani et al., (2013)
Palm kernel trunk	34.5	31.8	25.7	2.7	4.3	13.0*	Kelly-Yong et al., (2007)
Palm mesocarp fibre	33.9	26.1	27.7	6.9	3.5	13.1	Kelly-Yong et al., (2007)
Soft wood	37.5	27.5	28.5	2.5*	3.5*	14.0*	McKendry, (2002)
Hard wood	47.5	27.5	22.5	2.5*	3.5*	14.0*	McKendry, (2002)

* assumption based on element properties of similar biomass species for case study illustration

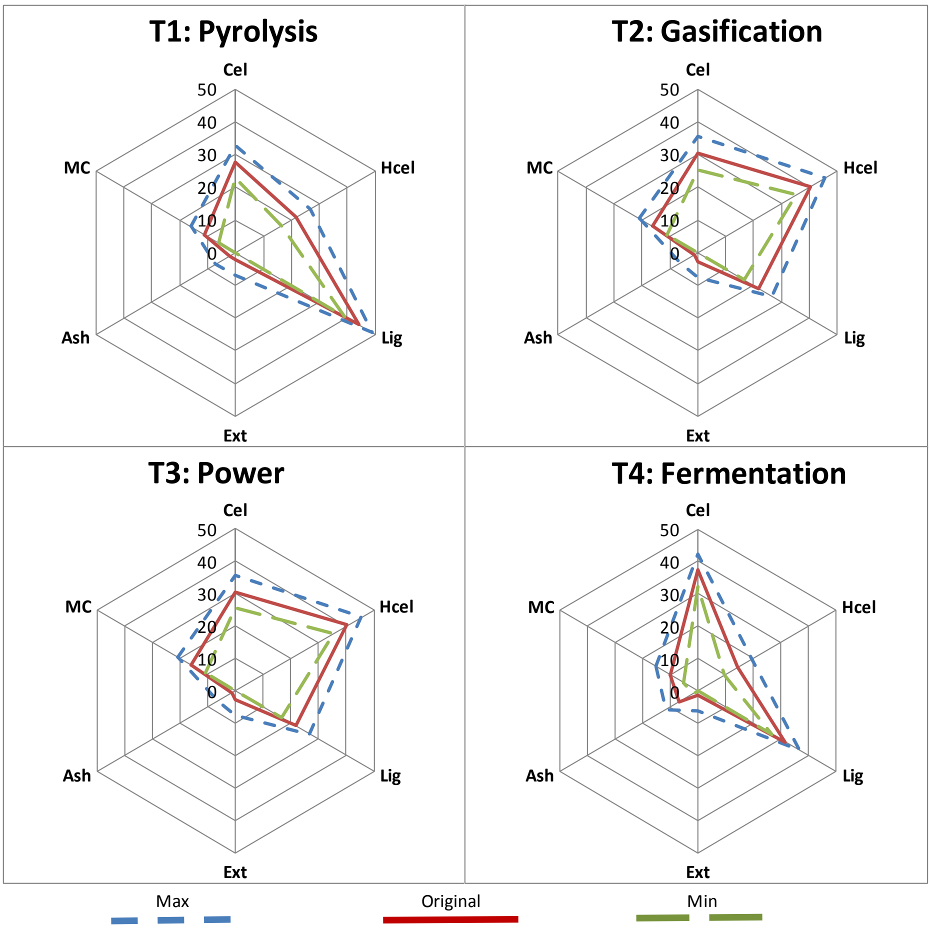


Figure 6- 2: Element acceptance range for each process technology in case study

Once the data compilation completed, information is transformed into supply chain optimisation model to determine the optimum supply chain network for the regional system. In other to demonstrate the difference between the proposed DRVT approach and the conventional approach (discussed in Chapter 2), 4 sub-case studies are suggested as shown in Tables 6-4(a) and Table 6-4(b) which summarise the comparison between both approaches. Sub-case studies 1A and 1B evaluate the differences between both models in the scenario where exportation of biomass is not considered; while sub-case studies 2A and 2B evaluate both models in the scenario where exportation of biomass is considered. Since the main objective of the research is focus on the improvement of feedstock

Table 6- 4(a): Sub-case study scenarios

Scenarios	(A) Conventional Supply Chain Model	(B) DRVT Approach Supply Chain Model
(1) Only and must fulfil local demand (does not consider exportation)	1A	1B
(2) Must fulfil local demand and allow exportation	2A	2B

Table 6- 4(b): Comparisons between conventional and DRVT approach supply chain models

	(A) Conventional Supply Chain Model	(B) DRVT Approach Supply Chain Model
Feedstock selection platform	Based on biomass species	Based on biomass elemental properties
Potential feedstock option	Specific biomass species within the regional system	Any biomass species within the regional system
Supply chain network flexibility	Each plant has dedicated resource point	Each plant can freely determine the optimum biomass from the best resource point
Feedstock price	Restricted option, based on market price	More option, able to choose cheaper alternative feedstock based on market price

selection over existing regional biomass system, consideration of biomass feedstock will based on the respective technologies, which in this case is based on literature. Following illustrates the concept differences and the translation into both models.

6.2.2.1 Conventional model formulation

In order to derive the conventional model formulation for biomass feedstock selection, it is important to analysis the feedstock selection criteria for the existing technologies. Based on Table 6-2, conversions yield of all four process technologies are developed based on feedstock weight. Each technology has dedicated original feedstock. This demonstrates the problem in some of the biomass technologies, where the development is only based on a specific biomass species. Impact of integrating alternative biomass into the system is unknown. Thus, when translate into supply chain optimisation model, only the original biomass feedstock species, palm shell, oil palm frond, and palm oil empty fruit bunch (EFB), are considered in respective technology as shown in the superstructure in Figure 6-3. Palm kernel trunk, palm mesocarp fibre, soft wood, and hard wood are unable to integrate into the system due to unknown impact to the existing process technology. Thus in this case, these biomasses are considered as *underutilised biomass*.

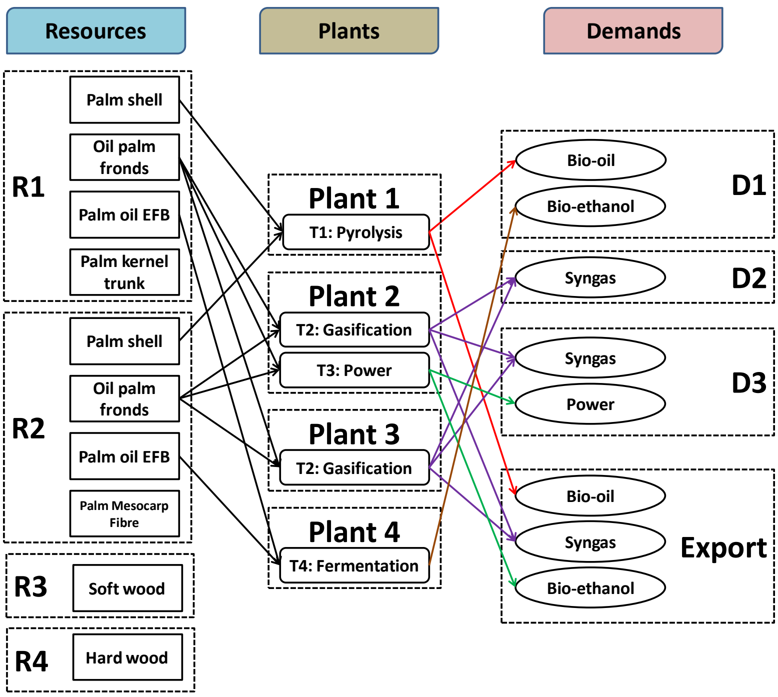


Figure 6- 3: Generic superstructure for convention biomass supply chain optimisation model

When translate this concept into the mathematical model, the upper and lower boundaries for the element acceptance range of respective technology (Equations 6-3 and 6-4) are set to be the same value as the original feedstock element characteristics in Table 6-3. Alternatively, since the technologies are incapable to accept underutilised biomasses, the model is unable "see" them as a potential feedstock. Thus, availability of underutilised biomasses within the system is presumed to be zero. In terms of the model translation in different exportation scenarios, the market demand at "Export" point in sub-case studies 1A and 1B are set to zero to show exportation is not considered; while a huge (infinite) value is implied in cases 2A and 2B to show the consideration of exportation without limitation. On the other hand, since only one mode of transportation (by truck) is considered in this case studies, the transportation cost Equations 6-10 and 6-11 can be simplified as below, where Transcost is equals to RM 0.5 per ton of material per kilometre transported. Please refer to Appendix I for complete model coding.

$$\sum_{m=1}^{M} \text{EleRecT}(m,e,j) \leq \text{E\_upper}(e,j) \times \text{TMatRecT}(j) \quad \forall\, j \qquad \textit{Reproduced from } (6\text{-}3)$$

$$\sum_{m=1}^{M} \text{EleRecT}(m,e,j) \geq \text{E\_lower}(e,j) \times \text{TMatRecT}(j) \quad \forall\, j \qquad \textit{Reproduced from } (6\text{-}4)$$

$$\sum_{m=1}^{M} RtoT(i,m,j) \times \text{Distance\_RtoT}(i,j) \times \text{Transcost} = \text{Cost\_RtoT}(i,j) \quad \forall\, i,j \qquad \text{Simplified } (6\text{-}10)$$

$$\sum_{m=1}^{M} TtoD(jp,m,k) \times \text{Distance\_TtoD}(jp,k) \times \text{Transcost} = \text{Cost\_TtoD}(jp,k) \quad \forall\, jp,k \qquad \text{Simplified } (6\text{-}11)$$

6.2.2.2 Demand-Resources Value Targeting model formulation

In contrast with the conventional approach, DRVT model inherits the concept of element targeting, where the selection of biomass is based on feedstock element characteristics. As discussed previously, the element acceptance range of respective technologies in this case study are assumed to be ±5% (Figure 6-2), which is based on the natural biomass properties fluctuation. This platform enables the model to consider underutilised biomass and determine the optimum feedstock ratio without affecting the process performance. Figure 6-4 shows the superstructure of DRVT model for this case study.

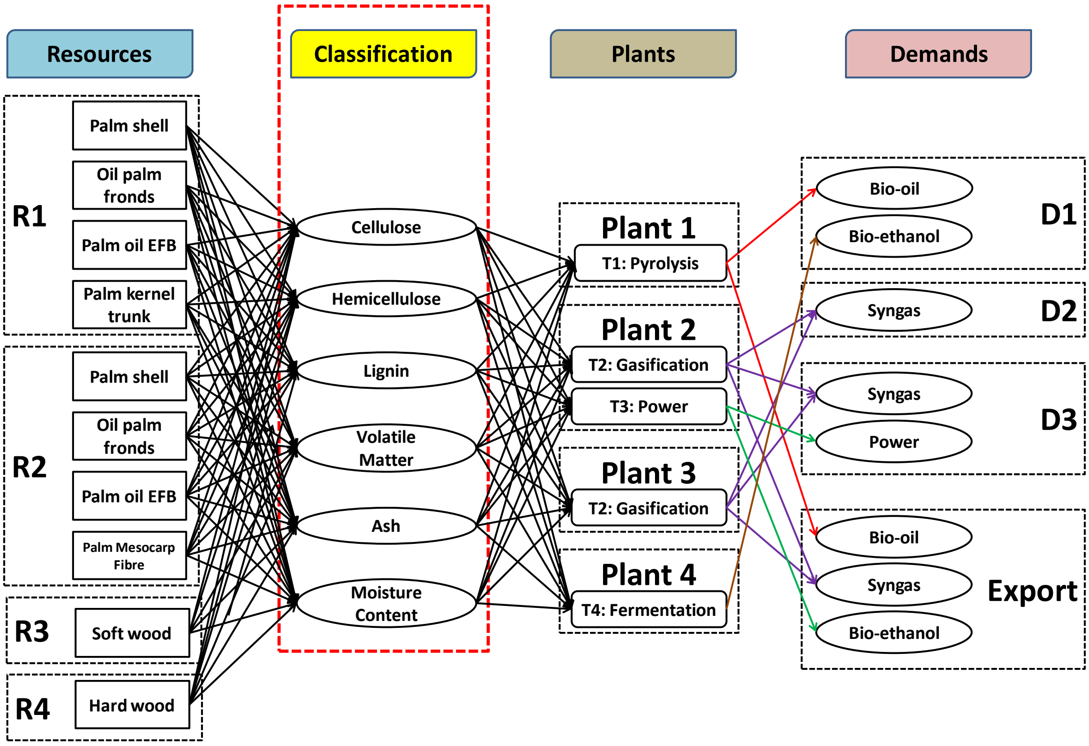


Figure 6- 4: Superstructure for Demand-Resources Value Targeting model

When translate to the model, the upper and lower boundaries of element acceptance range for each technology is tabulated as per Table 6-5. Similar approach as discussed above is applied in order to demonstrate the different scenarios of sub-cases 1B and 2B. Simplified transportation cost calculation (Simplified Equations 6-10 and 6-11) also implied in this model for consistency of comparison with the conventional model. Since the product generation for all process technologies are estimated based on feedstock weight, the first term in Equation 6-7 is not applicable for this case study.

Table 6- 5: Element acceptance range of each technology

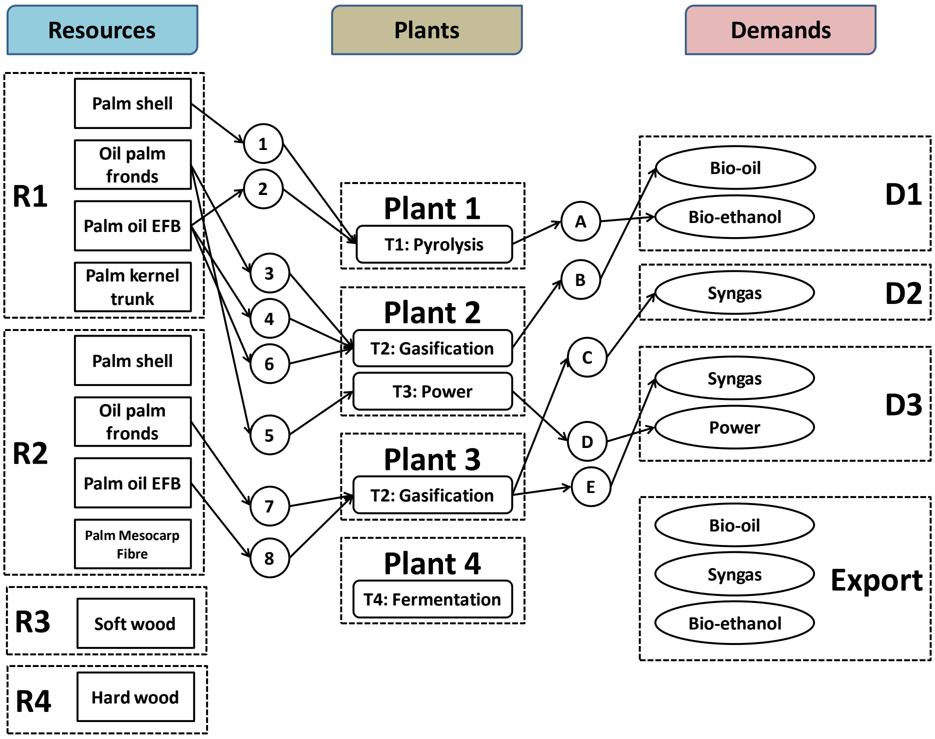
Technology	Boundary	Biomass Element Characteristics (wt%)					
		Cel	Hcel	Lig	Ext	Ash	MC
T1	Upper	32.7	26.6	49.0	7.0*	7.1	16.0
	Lower	22.7	16.6	39.0	0.0	0.0	6.0
T2	Upper	35.4	45.4	26.7	7.7	6.3	21.0
	Lower	25.4	35.4	16.7	0.0	0.0	11
T3	Upper	35.4	45.4	26.7	7.7	6.3	21.0
	Lower	25.4	35.4	16.7	0.0	0.0	11
T4	Upper	42.3	19.6	36.7	6.3	11.7	15.0
	Lower	32.3	9.6	26.7	0.0	1.7	5.0

6.2.3 Model problem statement

The case studies were solved to maximised Totalprofit using General Algebraic Modeling System (GAMS) software, version 23.4. The problem is solve via linear programming with CPLEX solver using Intel(r) Core(TM) i5-4200U CPU at 1.6 GHZ up to 2.30 GHz, 4 GB RAM memory and 64-bit Windows 8 system. A total of 21 blocks of equations and 18 blocks of variables are found within the model. The model will proposed the optimum solution for biomass distribution network from resources location to technology plants, and to demand locations. Utilisation of each available biomass species, including underutilised biomasses will be reflected via the proposed optimum supply chain network. Appendix I presented GAMS coding and result for all the sub-cases.

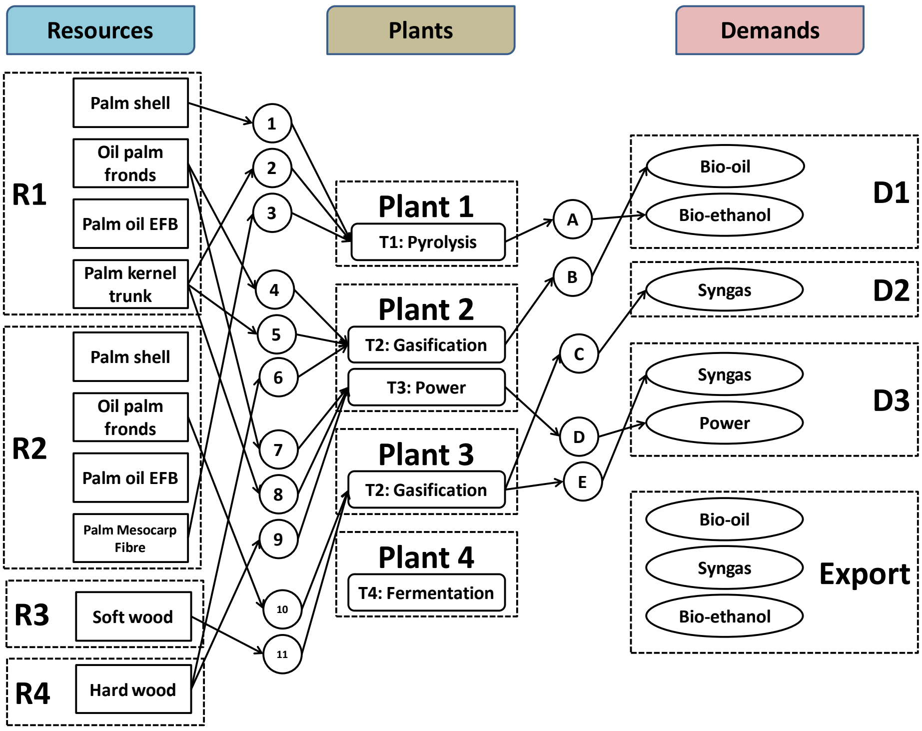
6.2.4 Results and discussions

Four sub-case studies were performed to demonstrate the advantages of DRVT approach in difference scenarios and compared to conventional optimisation approach. The main objective is to observe the improvement of DRVT approach over the conventional approach in terms of feedstock selection and consideration of underutilised biomass. Figures 6-5 to 6-8 show the optimum supply chain network of each sub-case study. Each figures also indicated the optimum amount of biomass or product transported from one location to another. Table 6-6 tabulates the overall utilisation of each biomass species at respective resources location and Table 6-7 summaries the total profit of each cases.



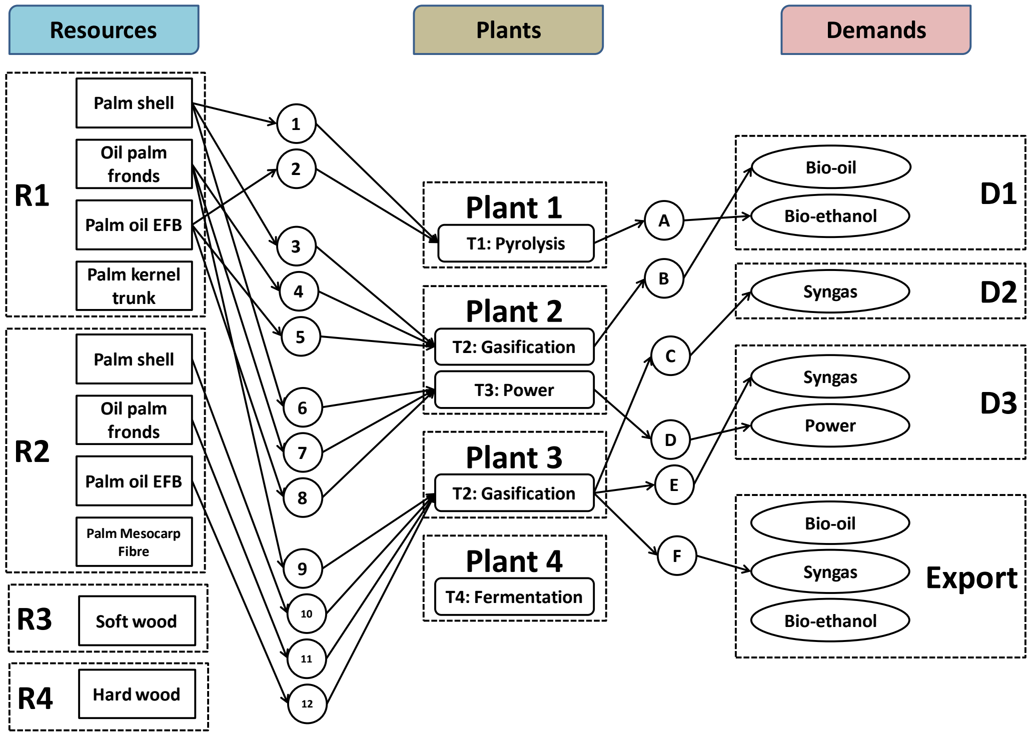
Indicator	1	2	3	4	5	6	7	8	A	B	C	D	E
Transported Material	1996 t	1367 t	665 t	160 t	94 t	23 t	95 t	23 t	1550 t	1600 t	860 N/m³	1200 MJ	350 N/m³

Figure 6- 5: Optimum supply chain distribution network for sub-case study 1A



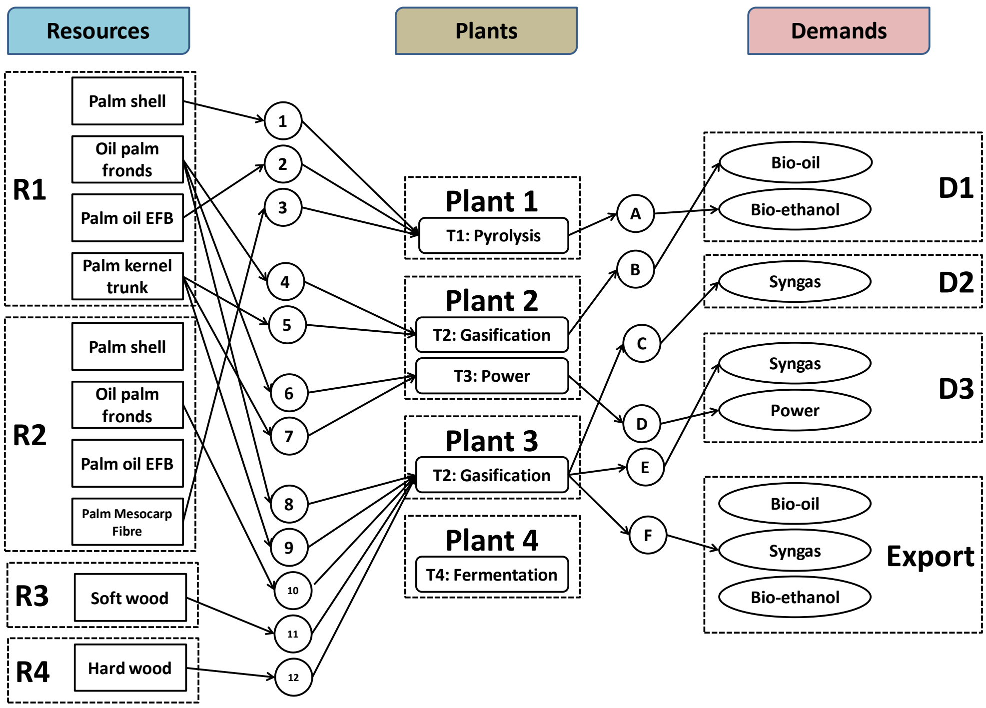
Indicator	1	2	3	4	5	6	7	8	9	10	11	A	B	C	D	E
Transported Material	2403 t	590 t	369 t	444 t	184 t	197 t	63 t	26 t	28 t	72 t	46 t	1550 t	1600 t	860 N/m³	1200 MJ	350 N/m³

Figure 6- 6: Optimum supply chain distribution network for sub-case study 1B



Indicator	1	2	3	4	5	6	7	8	9	10	11	12	A	B	C	D	E	F
Transported Material	1996 t	1367 t	168 t	619 t	37 t	24 t	88 t	5 t	793 t	840 t	2300 t	186 t	1550 t	1600 t	860 N/m³	1200 MJ	350 N/m³	41221 N/m³

Figure 6- 7: Optimum supply chain distribution network for sub-case study 2A



Indicator	1	2	3	4	5	6	7	8	9	10	11	12	A	B	C	D	E	F
Transported Material	2239 t	373 t	750 t	345 t	480 t	49 t	68 t	1106 t	253 t	2300 t	1500 t	541 t	1550 t	1660 t	860 N/m³	1200 MJ	350 N/m³	57492 N/m³

Figure 6- 8: Optimum supply chain distribution network for sub-case study 2B

Table 6- 6: Overall biomass utilisation at each resource location

Location	Biomass species	1A		1B		2A		2B	
		t/day	Utilisation	t/day	Utilisation	t/day	Utilisation	t/day	Utilisation
R1	Palm shell	1995.5	79.8%	2403.3	96.1%	2187.5	87.5%	2239.9	89.6%
	Oil palm fronds	758.8	50.6%	506.5	33.8%	1500	100%	1500.0	100%
	Palm oil EFB	1549.2	77.5%	-	-	1409.3	70.5%	372.9	18.6%
	Palm kernel trunk	-	-	799.7	99.9%	-	-	800.0	100%
R2	Palm shell	-	-	-	-	840.2	48.0%	-	-
	Oil palm fronds	94.7	4.1%	71.9	3.1%	2300	100%	2300.0	100%
	Palm oil EFB	22.8	1.1%	-	-	186.1	8.8%	750.0	35.7%
	Palm Mesocarp Fibre	-	-	368.9	49.2%	-	-	-	-
R3	Soft wood	-	-	45.5	3.0%	-	-	1500.0	100%
R4	Hard wood	-	-	224.9	12.9%	-	-	540.0	30.9%

Table 6- 7: Total profit for each sub-case study

	Sub-case			
	1A	1B	2A	2B
Total profit	RM -816k /day ($ -204k /day)	RM -756k /day ($ -189k /day)	RM 2576k /day ($ 644k /day)	RM 4053k /day ($ 1013k /day)

In both cases 1A and 2A of conventional biomass supply chain model, underutilised biomasses are not considered in the system. Therefore, many biomasses are not used to convert into higher value downstream products, leading to waste of resources. However, as compared to cases 1B and 2B, DRVT approach allows the consideration of underutilised biomass, resulting in higher quality of biomass supply chain integration. This leads to an improvement of the system as reflected in the total profit of the system increases as shown in Table 6-7. The profit increased by approximately 7.4 % in case 1 and 57.3 % in case 2.

By comparing case 1As with 1B and 2A with 2B respectively in Table 6-6, utilisation of each biomass species is generally increased. A point worth mentioning is that utilisation of some biomass species is reduced, such as oil palm fronds in case 1B compared to 1A, and palm oil EFB and palm shell from Resource 2. The reduction of oil palm fronds utilisation in the case is due to the relative higher price of oil palm fronds. With DRVT approach, the model choices alternative biomass species with lower cost as technology feedstock without compromising the technology yield to maximise total profit. In cases 2A and 2B, similarly, the reduction of biomass utilisation in palm oil EFB and palm shell is due to the relative higher cost. However, as oppose to previous case, palm oil fronds is fully utilised in both cases 2A and 2B. This due to the geographical aspect that Plant 3 which utilises palm oil fronds is nearer to the export location as compared to other plant. This allows more production at Plant 3 with less transportation cost to maximise total profit of the system.

By comparing case 1A with 2A and 1B with 2B, the result shows that by only fulfilling the local requirement, the system is unable to self sustain to achieve positive total profit. However, by considering the possibility of exportation, positive profit is achievable. Aside from that, this increases the utilisation of the resources available within the regional area. Table 6-6 shows a higher percentage of overall utilisation of biomass available. Aside from that, significant higher profit is obtained as shown in Table 6-7. This demonstrate that increasing production might able to improve the feasibility of implementation of biomass industry.

With the comparison of all four sub-case studies proposed, DRVT approach has proven to be able to improve existing biomass supply chain. Most of the improvements are due to the enhancement of feedstock selection to wider range of biomass species. This can be observed by comparing the distribution network of all sub-cases where the main differences are in between the integration of resources and process plant. Logistic network between process plant and market demand are remained consistent due to the lack of fluctuation in marker demand in this study. Also, based on Table 6-6, potential biomass species are able to be identified by looking at the level of utilisation. This provides a good platform as screening tool to determine potential alternative biomass species for future development. Nevertheless, more development can be considered in the optimisation model to further improve the system.

6.3 Biomass Element Cycle Analysis (BECA) optimisation approach

Previous discussion has shown the advantage of element targeting approach in enhancing the current biomass supply chain optimisation model. The main goal of DRVT approach is incorporate alternative upstream biomasses into the consideration of supply chain model. Nevertheless, further improvement of DRVT approach is possible to enhance application of element targeting approach in biomass supply chain optimisation.

Biomass Element Cycle Analysis (BECA) is proposed from inspiration of the combination of DRVT approach and Life Cycle Assessment (LCA) – applied in capturing carbon, water, nitrogen, sulphur, and other footprint (Shan et al., 2014). Concept of LCA also applied to conducted multi-objective model on relations between footprints within biomass energy supply chain (Čuček et al., 2012). Cradle-to-grave concept in LCA suggests that consideration of alternative biomass should not be limited to upstream biomasses from plantation only. Thus, similar to DRVT approach, BECA approach acts as a platform to investigate potential application of each biomass within a system. Nonetheless, the main improvement of BECA approach is further expanding feedstock consideration to also include process waste as potential underutilised biomass. It enables recycling loop of process waste as alternative potential feedstock within the system.

In BECA approach, each process stages within biomass industry are studied to evaluate potential re-utilisation of process waste. Many have conducted work converting process by product to downstream product such as energy (Klemeš and Varbanov, 2013). Element characteristics classification will be conducted on by-product (which is also a type of biomass) to allow wider coverage in the search for alternative resources and minimises waste management. Utilising resources from existing process waste is much economically efficient and environmental friendly. With the proposed BECA approach, utilisation of each potential biomass in the system can be well analysed, provide better understanding of the system resources and allows effective planning and development.

6.3.1 Methodology for Biomass Element Cycle Analysis approach

The general methodology of BECA approach is very similar to DRVT approach. Several modifications are conducted to include the consideration of process waste as potential technology feedstock.

6.3.1.1 Exploitation of regional biomass system

Similar to DRVT approach, BECA approach initiates with data collection based on regional biomass system, including available resources, existing process plants and technologies, market demands and logistic and location data (distance and cost of transportation). The main difference is in the review of existing process plants, waste production at each process stage will be evaluated based on availability amount and ease of collection. Potential process waste will be considered as alternative biomass feedstock for potential recycle use. Furthermore, BECA approach also considered production cost of each technology, hence, the data of production cost per unit product is required.

6.3.1.2 Identify biomass element characteristics

In this step, all available biomass properties are determined based on element characteristics as discussed in Section 6.2.1.2. Again, the main difference between DRVT approach and BECA approach is the determination of process waste element characteristics. This will allow the model to consider process waste as part of the alternative biomasses within the system for potential recycle use.

6.3.1.3 Identify technology element acceptance range

Methodology to construct element acceptance range for each technology in BECA approach is identical to DRVT approach, where concept has been discussed in Chapter 3.

6.3.1.4 Integration into the Biomass Element Cycle Analysis model

Several modifications are introduced based on the mathematical formulation of DRVT model to construct BECA model. Following describe in detail on all equations in BECA model.

Element constraint:

All the equations for element constraint to provide a systematic platform for biomass selection in DRVT model are applicable in BECA model. Thus, Equations 6-1 to 6-4 are used in BECA model as well. Equation 6-1 indicates the calculation of total biomass element, ***e*** received in each process plant, ***j*** for each biomass, ***m***, $\mathrm{EleRecT}(m, e, j)$ based on biomass, ***m*** received at process plant, ***j*** $\mathrm{MatRecT}(m, j)$ and biomass element characteristics, $\mathrm{Element}(m, e)$.

$$\mathrm{MatRecT}(m, j) \times \mathrm{Element}(m, e) = \mathrm{EleRecT}(m, e, j) \quad \forall\, m, e, j$$ *Reproduced from* (6-1)

Equation 6-2 indicates total biomass received at process plant, ***j***, $\mathrm{TMatRec}(j)$ by combining each biomass ***m***, at each process plant ***j***, $\sum_{m=1}^{M} \mathrm{MatRecT}(m, j)$.

$$\sum_{m=1}^{M} \mathrm{MatRecT}(m, j) = \mathrm{TMatRecT}(j) \quad \forall j$$ *Reproduced from* (6-2)

Equation 6-3 indicates total biomass element characteristic, ***e*** received in process plant, ***j***, $\sum_{m=1}^{M} \mathrm{EleRecT}(m, e, j)$ should be less than the upper limit of element acceptance range, ***e*** at respective process plant, ***j***, $\mathrm{E\_upper}(e, j)$ multiply with total biomass received at process plant, ***j***, $\mathrm{TMatRec}(j)$.

$$\sum_{m=1}^{M} \text{EleRecT}(m,e,j) \le \text{E\_upper}(e,j) \times \text{TMatRecT}(j) \quad \forall\, e,j \qquad \textit{Reproduced from } (6\text{-}3)$$

Similarly, Equation 6-4 indicates total biomass element characteristic, ***e*** received in process plant, ***j***, $\sum_{m=1}^{M} \text{EleRecT}(m,e,j)$ should be more than the lower limit of element acceptance range, ***e*** at respective process plant, ***j***, $\text{E\_lower}(e,j)$ multiply with total biomass received at process plant, ***j***, $\text{TMatRec}(j)$.

$$\sum_{m=1}^{M} \text{EleRecT}(m,e,j) \ge \text{E\_lower}(e,j) \times \text{TMatRecT}(j) \quad \forall\, e,j \qquad \textit{Reproduced from } (6\text{-}4)$$

<u>Mass constraint:</u>

In this section, several modifications are conducted based on DRVT model formulation to enhance the model integration by introducing recycle loop to recycle process waste as potential technology feedstock. Equation 6-5 is remain unchanged, which restricts total amount of each biomass, ***m*** sent from resource location, ***i***, $\sum_{j=1}^{J} RtoT(i,m,j)$ cannot more than total biomass available at each resource location, ***i***, $\text{Resource}(i,m)$.

$$\sum_{j=1}^{J} RtoT(i,m,j) \le \text{Resource}(i,m) \quad \forall\, i,m \qquad \textit{Reproduced from } (6\text{-}5)$$

Equation 6-6 in DRVT model is modified into Equation 6-15 below. $\sum_{jp=1}^{JP} TtoT(jp,m,j)$ represents the material, ***m*** transported from process plant output, ***jp***, to process plant input, ***j***. $TtoTfactor(m,j)$ is a parameter introduced as decision factor on which material, ***m***, should be considered in the recycle loop since ***m*** is representing both feedstock and product in the model. For all biomass and potential process waste, ***m*** are assigned value of "1", while the product, ***m*** will assigned as "0" such that the model do not recycle product as feedstock. Thus, the overall material received at process plant input, $MatRecT(m,j)$ is the summation of upstream biomass received, $\sum_{i=1}^{I} RtoT(i,m,j)$, and biomass recycled, $\sum_{jp=1}^{JP} TtoT(jp,m,j)$.

$$\sum_{i=1}^{I} RtoT(i,m,j) + \sum_{jp=1}^{JP} [TtoT(jp,m,j) \times TtoTfactor(m,j)] = MatRecT(m,j) \quad \forall\, m,j \qquad (6\text{-}15)$$

Equation 6-7 in DRVT approach is applicable in BECA approach, where the first term is to determine the product generation of process plant based on developed relation between feedstock element characteristics, and the second term is to determine the generation rate based on feedstock weight.

$$\sum_{j=1}^{J}\left[\sum_{\mathrm{m}=1}^{\mathrm{M}} \mathrm{EleRecT}(m,"e=e","j=j") \times ele\_\mathrm{yield}("j{=}j",m,jp)\right]$$

Reproduced from

$$+\sum_{j=1}^{J}[\mathrm{TMatRecT}("j=j") \times mass\_\mathrm{yield}("j{=}j",m,jp)] \quad (6\text{-}7)$$

$$= \mathrm{MatGenT}(m,jp) \qquad \forall\, m, jp$$

However, Equation 6-8 in DRVT approach is modified into Equation 6-16, which constraints the total material generated (product and by-product), $MatGenT(m,jp)$ has to be equal or more than the summation of material transported to demand, $\sum_{k=1}^{K} TtoD(jp,m,k)$ and material recycled to process plant, $\sum_{j=1}^{J} TtoT(jp,m,j)$

$$\sum_{k=1}^{K} TtoD(jp,m,k) + \sum_{j=1}^{J} TtoT(jp,m,j) \le MatGenT(m,jp) \quad \forall\, m, jp \qquad (6\text{-}16)$$

Equation 6-9 in DRVT model is applicable in BECA model, stated that total production of each process plant, $\sum_{j=1}^{J} TtoD(jp,m,k)$ has to fulfil minimum local market demand, $\mathrm{Lower\_Demand}(m,k)$. Excess production will be exported to other region with the limitation of $\mathrm{Upper\_Demand}(m,k)$. In case of no constraint for exportation, an immense value of material, ***m*** is assigned in the export location, ***k*** in $\mathrm{Upper\_Demand}(m,k)$.

Reproduced from

$$\mathrm{Lower\_Demand}(m,k) \le \sum_{j=1}^{J} TtoD(jp,m,k) \le \mathrm{Upper\_Demand}(m,k) \quad \forall\, m, k \qquad (6\text{-}9)$$

<u>Cost calculation:</u>

Due to the introduction of the recycle loop, cost calculation in BECA model is modified. Equation 6-10 and Equation 6-11 are still applicable in this model. Equation 6-10 indicates the transportation cost of sending biomass, ***m*** from resources location, ***i*** to process plant, ***j***, $\mathrm{Cost\_RtoT}(i,j)$ based on total biomass,

m from resources, ***i*** to process plant, j, $\sum_{m=1}^{M} RtoT(i,m,j)$, distance between resource, ***i*** and process plant, ***j*** based on transportation mode, ***r*** $\text{Distance\_RtoT}(i,j,r)$ and the flat rate transportation cost of the particular transportation mode, $\text{Transcost}(r)$, in \$ /t/km. Equation 6-11 indicates transportation cost of sending product, ***m*** from process plant output, ***jp*** to market demand, ***k***, $\text{Cost\_TtoD}(jp,k)$ based on total biomass, ***m*** from process plant output, ***jp*** to demand, k, $\sum_{m=1}^{M} TtoD(jp,m,k)$, distance between process plant, ***jp*** and demand, ***d***, $\text{Distance\_TtoD}(jp,k,r)$ based on the transportation mode, ***r*** and flat rate transportation cost of the particular transportation mode, $\text{Transcost}(r)$, in \$ /t/km.

$$\sum_{m=1}^{M} RtoT(i,m,j) \times \sum_{r=1}^{R} [\text{Distance\_RtoT}(i,j,r) \times \text{Transcost}(r)] = \text{Cost\_RtoT}(i,j) \qquad \forall\, i,j \qquad \textit{Reproduced from } (6\text{-}10)$$

$$\sum_{m=1}^{M} TtoD(jp,m,k) \times \sum_{r=1}^{R} [\text{Distance\_TtoD}(jp,k,r) \times \text{Transcost}(r)] = \text{Cost\_TtoD}(jp,k) \qquad \forall\, jp,k \qquad \textit{Reproduced from } (6\text{-}11)$$

Equation 6-17 is introduced to consider the transportation cost for the recycled material. This equation indicates transportation cost of sending product, ***m*** from process plant output, ***jp*** to process plant input, ***j***, $\text{Cost\_TtoD}(jp,j)$ is based on total biomass, ***m*** from process plant output, ***jp*** to process plant, ***j***, $\sum_{m=1}^{M} TtoD(jp,m,j)$, distance between process plant output, ***jp*** and process plant input, ***j***, $\text{Distance\_TtoT}(jp,j,r)$ based on the transportation mode, ***r*** and flat rate transportation cost of the particular transportation mode, $\text{Transcost}(r)$, in \$ /t/km.

$$\sum_{m=1}^{M} TtoD(jp,m,j) \times \sum_{r=1}^{R} [\text{Distance\_TtoT}(jp,j,r) \times \text{Transcost}(r)] = \text{Cost\_TtoD}(jp,j) \qquad \forall\, jp,j \qquad (6\text{-}17)$$

With respect to the introduction of Equation 17, Total transportation cost of the system, TTranscost is modified into Equation 6-18, which is the summation of $\text{Cost\_RtoT}(i,j)$, $\text{Cost\_TtoD}(jp,k)$ and $\text{Cost\_TtoD}(jp,j)$.

$$\sum_{\text{i,j}=1}^{\text{I,J}} [\text{Cost\_RtoT}(i,j)] + \sum_{\text{jp,k}=1}^{\text{JP,K}} [\text{Cost\_TtoD}(jp,k)] + \sum_{\text{jp,j}=1}^{\text{JP,J}} [\text{Cost\_TtoD}(jp,j)] = \text{TTranscost} \qquad (6\text{-}18)$$

BECA model introduced Equation 6-19 to consider total production cost, $TotProCost$ based on total material generated, $MatGenT(m, jp)$ multiply with the respective cost, $MatProCost(m, jp)$.

$$\sum_{m,jp=1}^{M,JP} [MatGenT(m, jp) \times MatProCost(m, jp)] = TotProCost \tag{6-19}$$

Thus the $Gross\ profit$ calculation is modified from Equation 6-13 to Equation 6-20 below. Note that the selling price for product, ***m***, in $Value(m)$ is not BECA model introduced Equation 6-19 to consider total production cost, $TotProCost$ based on total material generated, $MatGenT(m, jp)$ multiply with the respective cost, $MatProCost(m, jp)$. Noted that $\mathrm{Value}(m)$ is refer to the price of raw biomass (excluding transportation cost) and gross profit of product (excluding transportation cost, raw material cost and production cost).

$$\begin{aligned} \mathrm{Profit} = \sum_{m=1}^{M} \left[\left(\sum_{jp,k}^{JP,K} TtoD(jp, m, k) \right) \times Value(m) \right] \\ - \sum_{m=1}^{M} \left[\left(\sum_{i,l}^{I,J} RtoT(i, m, j) \right) \times Value(m) \right] - TotProCos \end{aligned} \tag{6-20}$$

<u>Objective function:</u>

The objective function for BECA model is identical to DRVT mode. Equation 6-14 shows the overall total profit of the system, $\mathrm{Totalprofit}$ after consideration of total transportation cost, $\mathrm{TTranscost}$.

Maximising Totalprofit:

$$\mathrm{Totalprofit} = \mathrm{Profit} - \mathrm{TTranscost}$$ *Reproduced from* (6-14)

6.3.2 Demonstration case study for Biomass Element Cycle Analysis approach

Similar to the discussion of DRVT approach, implementation of BECA approach is illustrated in this section with a demonstration of regional biomass supply chain network. As discussed in the methodology, the regional biomass system is evaluated for information compilation. Figure 6-9 shows the Cartesian coordinate mapping of a biomass system.

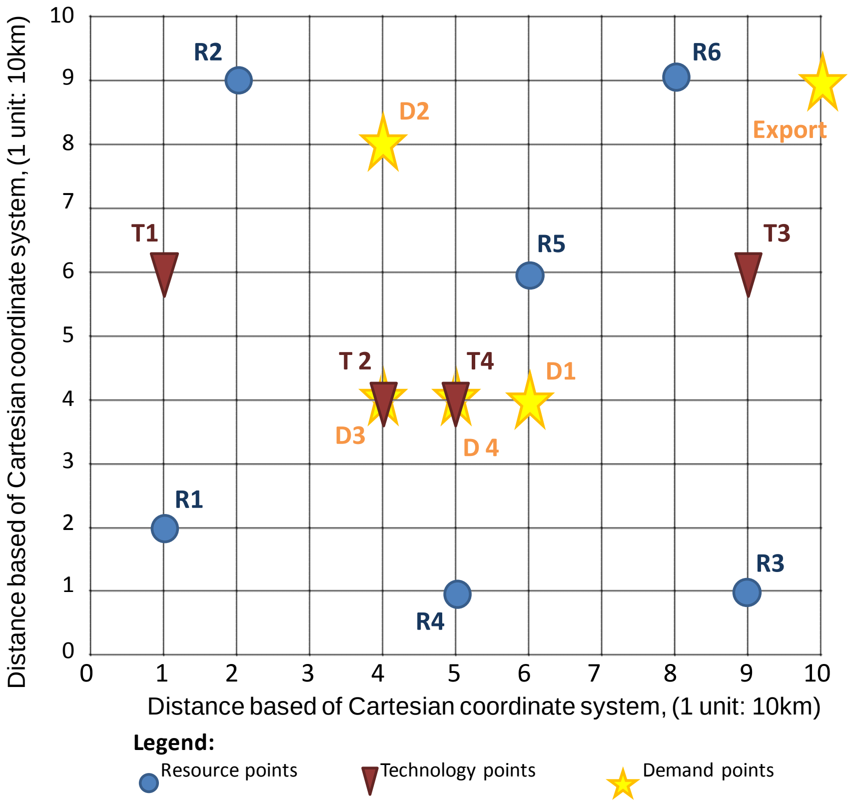


Figure 6- 9: Mapping for regional biomass system

Each dot (R1, R2, R3, R4, R5 and R6) in Figure 6-9 represents the collection points of upstream biomass available in the region. Table 6-8 shows the availability of each biomass species at each location and their respective price. The biomass available consists of corn cob, pine wood, treated wood, hazelnut shell, tomato residue and cauliflower residue. Price of corn cob is obtained from Erickson and Tyner, (n.d.) as $ 100 /t, which is based on the harvesting cost. Comparable value of $ 82.19 - 100.56 /t is reported by Thompson and Tyner (2014) for harvesting cost of corn stover as both biomasses are corn based biomass. Price of pine wood in from $ 160 - 220 /t is obtained based on pellet pine wood from industrial supplier (Alibaba.com, 2015) as a reference for the case study. The average cost of $ 190 /t is used in the case study. The price of treated wood, hazelnut shell, tomato residue and cauliflower residue are assumed to be about 25 % of the price of corn cob and pine wood. This is due to the relatively low demand and application in general. In addition, minimum harvesting effort is required as the existing disposal location can be utilised as collection point. For example, hazelnut shell, tomato residue and cauliflower residue can be collected from farm or food process plant. Treated wood can be collected from furniture plant. The price is mainly to cover the additional labour cost such as biomass collection. Transportation cost from resource point to process plant will be calculated based on the travelled distance, which will be determined by the model.

Table 6- 8: Availability of biomass and price

Location	Biomass species	Availability (t/d)	Selling price ($/t)
R1	Corn cob	3,000	100
R2	Pinewood	2,400	190
	Treated wood	500	47.5
R3	Hazelnut shell	300	40
R4	Tomato residue	950	30
R5	Cauliflower residue	500	25
R6	Treated wood	1,500	47.5

The triangular points (T1, T2, T3, and T4) in Figure 6-9 represents the location of processing plant for each technology stated in Table 6-9 respectively. In this demonstration, the capacity of the plant is not limited. In this biomass regional system, Technology 1 and Technology 2 are developed based on a specific biomass species, which are corn cob and pinewood respectively. Since BECA approach also considered potential process waste recycled from each process stage, gasification particle from Technology 2 is reported to have potential application due to high heat value (Miguel et al., 2012). Thus, it will be considered as an alternative biomass feedstock in this case study. On the other hand, Technology 3 and Technology 4 have constructed a relation between feedstock properties to the process outputs. Bio-ethanol production yield can be estimated based on the feedstock cellulose and hemicellulose content, while the produced heat value in Technology 4 is predicted based on feedstock heat value and moisture content.

Since BECA approach also considered the production cost for each technology, the information is estimated and summarised in Table 6-10. The cost is estimated based on the investment cost and operating cost. Biomass and transportation costs are excluded in the production

Table 6- 9: Biomass technologies and conversion data.

No.	Technology	Feedstock	Conversion Yield	Reference
1	Hydrogen Production Plant – Supercritical Water Gasification	Corn cob	30.46 g of H_2/kg of feedstock	Lu et al. (2012)
2	Gasification Power Plant	Pinewood	68% of feedstock heat value and 0.056 kg of particle/ kg of feedstock	Miguel et al. (2012)
3	Bio-ethanol Fermentation Plant	Bermudagrass, reed and rapeseed	0.29 kg of bio-ethanol/kg of cellulose and 0.23 kg of bio-ethanol /kg of hemicellulose	Goh et al. (2010) and Li et al. (2009)
4	Combustion Power Plant	Cellulosic biomass	30% of feedstock heat value (feedstock moisture content less than 50 wt%)	Mohammed et al. (2011)

cost calculation as both the costs will be added based on the biomass supply chain network calculated by the model. According to Lu et al. (2011), total hydrogen production cost including biomass and transportation cost is estimated to be \$ 6.15 /kg. Excluding the biomass and transportation cost, the production cost of hydrogen is assumed to be about 80 % of the proposed cost. Thus, the production cost of Technology 1 is estimated to be \$ 4.92 /kg. For technology 2, the production cost is estimated based on the economic analysis conducted by Wu et al., (2002). The capital cost of 1MW gasification and generation plant is estimated to be about \$ 367.2k. Operation cost is estimated to be around \$ 114k per year. With assumption of 15 operating years with average annual electricity output of 6500 MWh/y, and inflation of 30 % from 2002 to 2015, the production cost is estimated to be \$ 0.07 / kWh or \$ 0.019 /MJ. Production cost of Technology 3, bio-ethanol fermentation plant, is estimated based on Quintero et al. (2013). The total production cost is reported to be \$ 0.58 /L, which is approximate \$ 0.74 /kg. Out of the total production cost, 33 % is contributed by the raw material cost (biomass). Thus, the production cost excluding biomass and transportation cost is estimated to be \$ 0.57 /kg of ethanol produced. As for the production of Technology 4 combustion power plant, it is assumed to be 80% of the production cost of gasification power plant in Technology 2. Thus, the production cost is estimated to be \$ 0.0152 /MJ.

Table 6- 10: Production cost of each process plant

No.	Technology	Production cost (excluding biomass and transportation cost)
1	Hydrogen Plant	$ 4.92 /kg
2	Gasification Power Plant	$ 0.07 /kWh or $ 0.019 /MJ
3	Bio-ethanol Fermentation Plant	$ 0.57 /kg
4	Combustion Power Plant	$0.049 /kWh or $ 0.0152 /MJ

Lastly, the information of market demand in the regional biomass system is evaluated. Downstream product market demand locations are represented by "star" in Figure 6-9. Four local market demands (D1, D2, D3 and D4) available in the system and an export point (Export) to export excess products to other region. Table 6-11 shows the market demand of each product on the respective demand location. All local demands must be fulfilled. Profit of selling each unit product at respective location excluding transportation cost is also tabulated in Table 6-11. Each selling price is based on market value. According to ITM Power, hydrogen price is reported as $ 9.57 /kg in 2012 (Green Car Congress, 2015). Price of power supply is based on the latest 2014 tariff by Tenaga National, the main power supplier in Malaysia. Based on Department of Agriculture from Republic of Philippines, the latest bio-ethanol price by May 2015 is reported to be $ 1.24 /L, equivalent to $ 1.57 /kg (SRA , 2012). Similar to the case study in DRVT approach, this research does not focus on the different mode of transportation in the system. Thus, the case study is simplified into one type of transportation mode, which is truck with the logistic cost of $ 0.0001 /t/km.

Table 6- 11: Market demands and gross profit per unit product

Location	Product	Demand	Profit
Demand 1	Hydrogen	5 t/d	$ 10 /kg
	Bio-ethanol	15 t/d	$ 1.57 /kg
Demand 2	Hydrogen	20 t/d	$ 10 /kg
	Bio-ethanol	13 t/d	$ 1.57 /kg
Demand 3	Power	50 GJ /d **or** 13,888.9 kWh /d	$ 0.11 /kWh **or** $ 0.396 /MJ
Demand 4	Power	70 GJ /d **or** 19,444 kWh /d	$ 0.11 /kWh **or** $ 0.396 /MJ
Export	Hydrogen	unlimited	$ 10 /kg
	Bio-ethanol	unlimited	$ 1.57 /kg

Previous description has summarised the information compilation for the regional biomass system as per the methodology in Section 6.2.1.1. The next step is to compile the information of biomass element characteristics for the integration of element targeting approach into the system supply chain management. Table 6-12 summaries element characteristics of each resource based on literature, including the gasification particle from Technology 2 waste. However, some of the element properties are not reported in the respective literature. For the purpose of case study demonstration, the value is assumed and taken from similar species. Similarly, the heat value of biomass is estimated via Equation 4-1 proposed by Nhuchhen and Salam (2012) which derived from various biomass species such as hazelnut shell, corn cob, wood chips, pine wood, pine pellet. Figure 6-10 shows the radar chart of all biomass in the system to illustrate the unique properties of each biomass in a graphical approach.

Table 6- 12: Element characteristic of each biomass in the system

Biomass	Biomass element properties (wt%/wt%)							
	Ash	FC	VM	MC	HV***	Cellulose	Hemicellulose	Ref.
Corn cob	2.9	17.4	72.7	7.0	19.2**	30.0*	15.0*	Lu et al. (2012)
Pinewood	1.6	19.0	71.6	8.0	21.2	40.0*	20.0*	McKendry (2002)
Hazelnut shell	1.7	18.0*	73.5*	6.8	19.4**	38.2	12.1	Madenoğlu et al. (2011)
Tomato residue	3.7	16.5*	72.3*	7.5	19.0**	24.0	17.0	Madenoğlu et al. (2011)
Cauliflower residue	15.0	6.7*	66.3*	12.0	15.8**	31.1	5.4	Madenoğlu et al. (2011)
Treated wood	4.9	0.0	80.3	14.8	19.6	38.0*	25.0*	Vitasari et al. (2011)
Gasification particles	8.1	84.4	6.5	1.0	29.9	0	0	Miguel et al. (2012)

* assumption on element properties for case study illustration
** obtained from co-relation by Nhuchhen and Salam (2012)
*** unit of MJ/kg

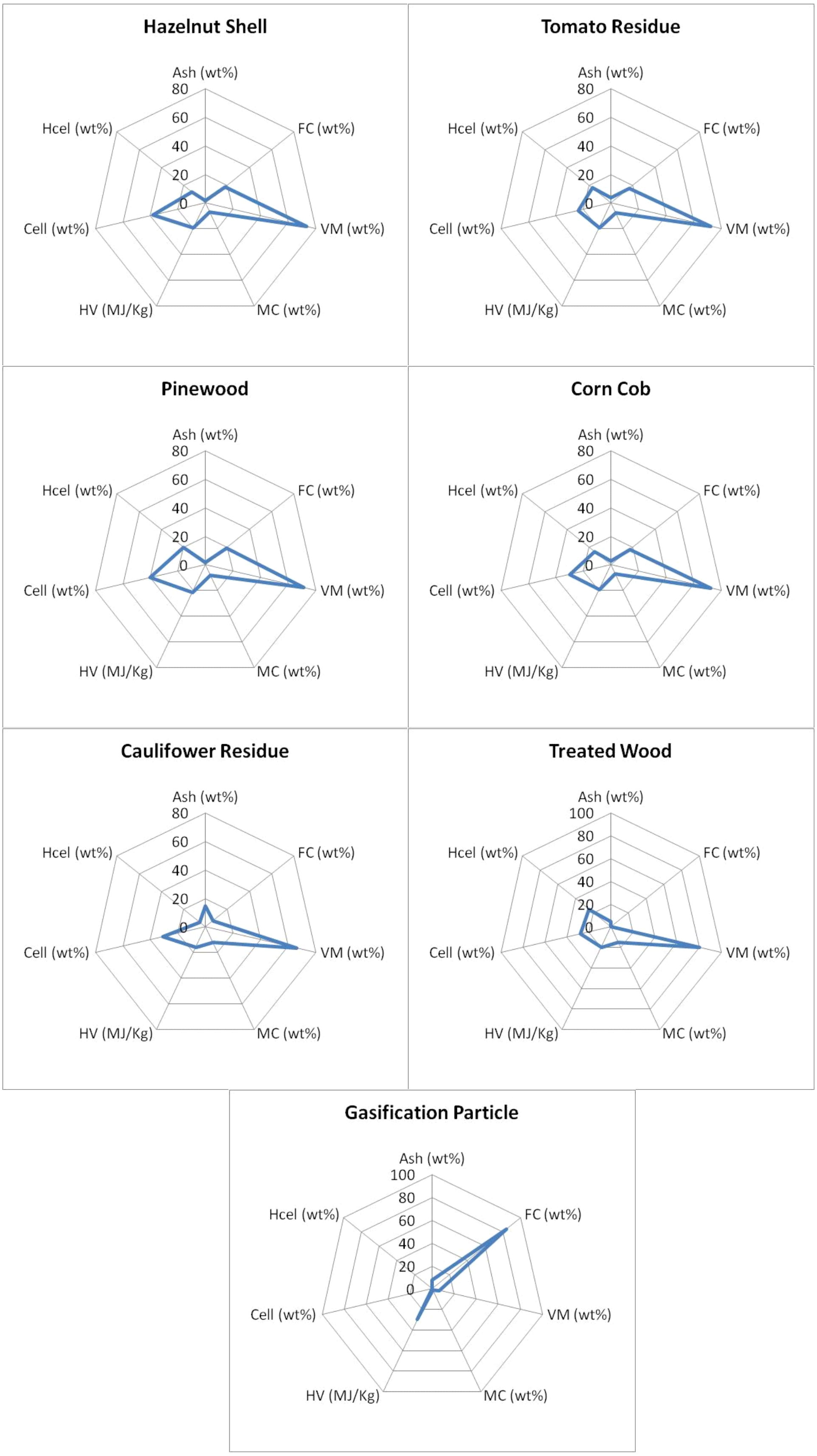


Figure 6- 10: Biomass element characteristic

$$HV = 20.7999 - 0.3214 \times \frac{VM}{FC} + 0.0051 \times \left(\frac{VM}{FC}\right)^2 - 11.2277 \times \frac{Ash}{VM} + 4.4953 \left(\frac{Ash}{VM}\right)^2 - 0.7223 \times \left(\frac{Ash}{VM}\right)^3 + 0.0383 \times \left(\frac{Ash}{VM}\right)^4 + 0.0076 \times \frac{FC}{Ash}$$

Reproduced from (4-1)

Next, the element acceptance range of each technology is constructed based on the literature. As shown in Table 6-9 above, Technology 1 and Technology 2 were developed based on corn cob and pinewood respectively. No study has conducted to evaluate the relation between feedstock element characteristics and process output. Nevertheless, both literatures have reported the properties of the original feedstock, as per Table 6-12. No analysis on which element is the key element of the process. Thus, all element characteristic reported in the literature are assumed to be equally important. Therefore, technology element acceptance is assumed based on a conservative assumption of element deviation factor, f_e of ±5 % for all element characteristic based on the original feedstock, which in this case Corn Cob and Pinewood respectively to ensure consistency of the process performance. This approach has been discussed in detail in Chapter 3, Section 3.4.2.

On the other hand, the original biomass feedstock for Technology 3 is not available in the system. However, both Technology 3 and Technology 4 had developed a process output prediction method based on specific feedstock properties. This approach of element acceptance range construction has been discussed in Chapter 3, Section 3.4.1. Goh et al. (2010) summarised that bio-ethanol conversion yield in fermentation (Technology 3) with respect to cellulose and hemicellulose content as described in Table 6-9, which based on several literatures including Li et al. (2009). Li et al. (2009) conducted laboratory test on simultaneous saccharification and fermentation on lignocellulosic biomass. The work included a pretreatment of biomass to remove undesirable element from the feedstock. This process step minimises and eliminates some uncertainty of feedstock, which allows only the key elements for Technology 3, subjected to cellulose and hemicellulose only. Although other element such as pH value is very critical in fermentation as it is affecting enzyme's activities, however it is noted that pH is part of the controlled parameter based on the work conducted by Li et al. (2009). Therefore, Technology 3 is assumed to have a pH control system. The remaining element characteristics are assumed will not significantly affecting the overall process, thus giving the element acceptance range of each element characteristic for Technology 3 in the range from 0 % to 100 %. Further experiment work should be conducted to analyse in detail the impact of other element characteristic to the overall process. Element acceptance range for any element characteristic that found to be significantly impacting the process should be considered in future work.

In Technology 4, combustion of biomass is highly dependent on heat value of biomass. Besides, combustion is only feasible when moisture content of feedstock is less than 50 wt% (Mohammed et al., 2011). Therefore, power output of Technology 4 will be based on feedstock biomass heat value and moisture content not more than 50 wt% in the feedstock. All technologies element acceptance range is presented in the form of radar chart in Figure 6-11. The “zoom in” portion of the figure is to emphasize on the small element acceptance range of the technology in this case study.

In the next step, all information collected is transformed into supply chain optimisation model. Three sub-case studies are conducted in this case study to compare between: i) Case A- conventional biomass supply chain optimisation approach, ii) Case B- DRVT approach, and iii) Case C- BECA approach. Table 6-13 summaries the differences of each approach and model formulation for each sub-case study is discussed below.

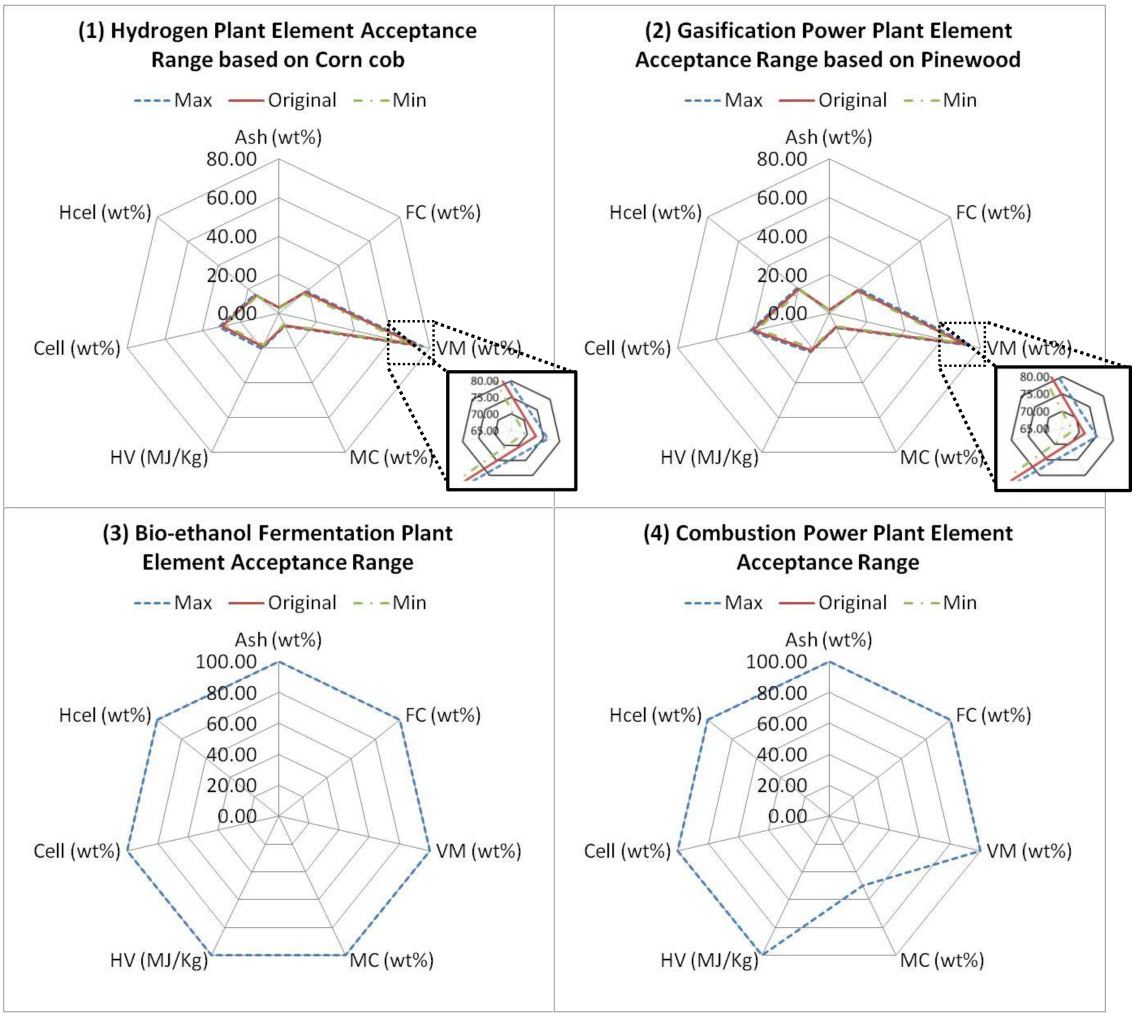


Figure 6- 11: Element acceptance range for each technology

Table 6- 13: Comparison of conventional, DRVT, and BECA approaches

Sub-Case	A	B	C
Approach	**Conventional**	**DRVT**	**BECA**
Optimisation of mainstream biomass distribution network	√	√	√
Integration of element targeting approach	X	√	√
Recirculation of downstream process waste	X	X	√

√: considered X: not considered

6.3.2.1 Conventional model formulation

As discussed in Chapter 2 literature review, the existing biomass supply chain optimisation model generally decide the technology feedstock based on the original biomass feedstock during the technology development. When we translate this conventional approach into superstructure model for this case study (Figure 12), treated wood, hazelnut shell, tomato residue and cauliflower residue will not be considered within the regional area due to unavailability of existing process plant that utilised respective biomass species.

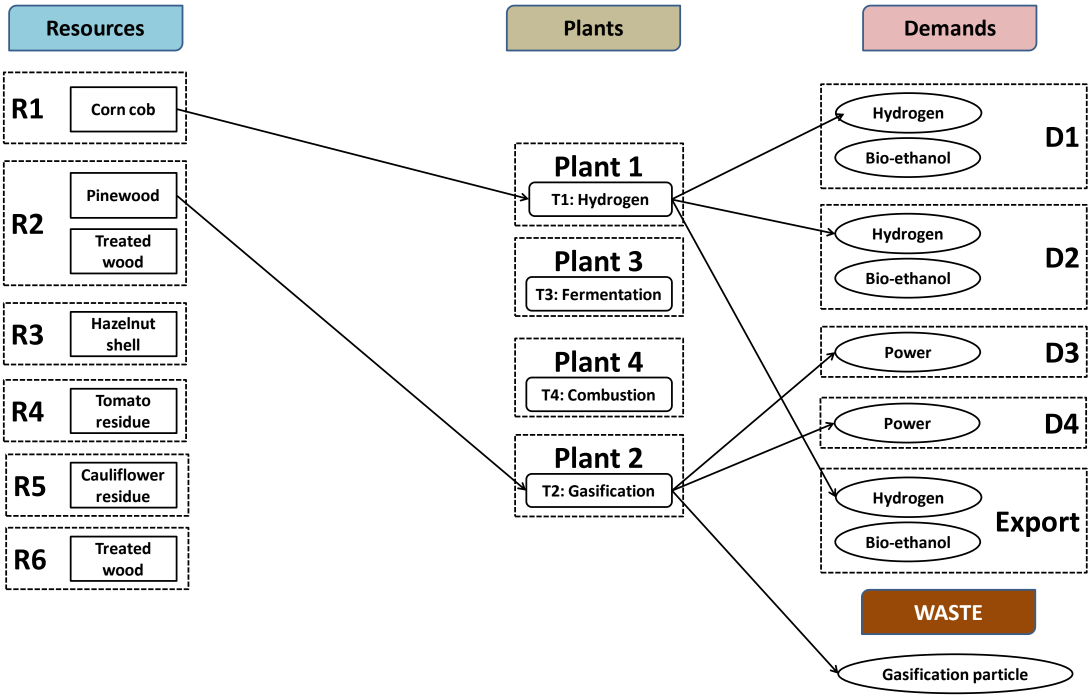


Figure 6- 12: Superstructure of biomass supply chain for conventional approach

However, outside of biomass supply chain optimisation development, Tang et al. (2013) proposed a conceptual integration approach based on bioprecursors (starch, hemicellulose, cellulose, lignin, triglycerides and protein) to determine the optimum biorefinery platform (sugar, thermochemical, biogas, and carbon-rich chains) for each biomass feedstock. The fundamental concept of the proposed work is very similar to the element targeting approach stated in Section 3.4.1, where the bioprecursors are similar to element characteristics and the biorefinery platforms are similar to technology element acceptance range. Nevertheless, the main objective of Tang et al. (2013) is to optimise biomass technology pathway, such that the optimum biomass technology is proposed with consideration biomass feedstock availability and uncertainties. Logistic issue such as resources-to-plant-to-demand location and transportation mode is not considered. Yet, this approach has the advantage to identify optimum process technologies during the design phase over the course of operating years. In contrast, the proposed concept of element targeting approach in this work focuses on the supply chain optimisation in existing regional system where all the process plants are pre-exist. Since the process technology is pre-fixed in the existing system, the proposed DRVT and BECA approach optimise the biomass feedstock selection based on logistic issue and biomass properties.

Nevertheless, with the consideration of the development in technology selection as proposed by Tang et al. (2013), the superstructure for the conventional biomass system integration for this case study is modified to Figure 13. All available biomass species (including process waste-gasification particle) are integrated into Technology 3 and Technology 4 since the feedstock selection criteria are based on biomass properties as stated in Table 6-9. Nonetheless, only the original feedstock is integrated into Technology 1 and Technology 2 as these technologies were developed based on biomass species (corn cob and pine wood respectively) without knowledge of the process impact due to feeding alternative feedstocks.

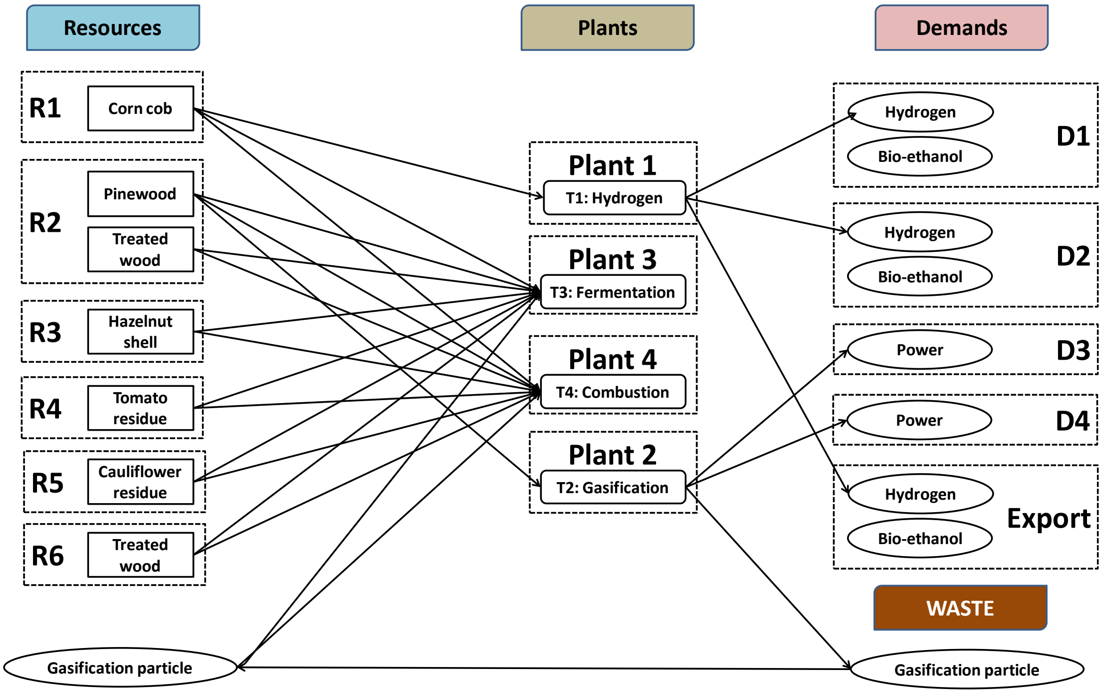


Figure 6- 13: Superstructure of biomass supply chain for conventional approach

Since Technology 1 and Technology 2 only will consider corn cob and pinewood as feedstock, the upper and lower boundaries of element acceptance range are set to be the same value as the original feedstock properties stated in Table 6-12. The total generation rate is based on total amount of biomass received at respective plant which represented by the second terms of $\sum_{j=1}^{J}[\text{TMatRecT}(\text{"}j = j\text{"}) \times \text{yield}(\text{"j=j"}, m, jp)]$ in Equation 6-7. On the other hand, the feedstock selection criteria Technology 3 and Technology 4 are based on biomass properties (element characteristics, ***e***), thus the production generation is determined based on the total element received at respective plant, $\sum_{j=1}^{J}[\sum_{\text{m}=1}^{\text{M}} \text{EleRecT}(m, \text{"}e = e\text{"}, \text{"}j = j\text{"}) \times \text{yield}(\text{"j=j"}, m, jp)]$. This case study has shown an example where both terms in Equation 6-7 are used to cater for different type of process technologies.

$$\sum_{j=1}^{J}\left[\sum_{\text{m}=1}^{\text{M}} \text{EleRecT}(m, \text{"}e = e\text{"}, \text{"}j = j\text{"}) \times \text{yield}(\text{"j=j"}, m, jp)\right] + \sum_{j=1}^{J}[\text{TMatRecT}(\text{"}j = j\text{"}) \times \text{yield}(\text{"j=j"}, m, jp)] = \text{MatGenT}(m, jp) \quad \forall\, m, jp$$

Reproduced from (6-7)

In addition, one mode of transportation is considered in this case study; hence the transportation cost Equations 6-10, 6-11 and 6-17 are simplified as below (one parameter in set ***r***).

$$\sum_{m=1}^{M} RtoT(i, m, j) \times \text{Distance\_RtoT}(i, j) \times \text{Transcost} = \text{Cost\_RtoT}(i, j) \quad \forall\, i, j$$

Simplified (6-10)

$$\sum_{m=1}^{M} TtoD(jp, m, k) \times \text{Distance\_TtoD}(jp, k) \times \text{Transcost} = \text{Cost\_TtoD}(jp, k) \quad \forall\, jp, k$$

Simplified (6-11)

$$\sum_{m=1}^{M} TtoD(jp, m, j) \times \text{Distance\_TtoT}(jp, j) \times \text{Transcost} = \text{Cost\_TtoD}(jp, j) \quad \forall\, jp, j$$

Simplified (6-17)

6.3.2.2 Demand-Resources Value Targeting model formulation

Figure 14 shows the superstructure model of DRVT approach for this case study. With the introduction of element targeting approach, DRVT uses biomass element characteristics as the feedstock selection platform. This enables Technology 1 and Technology 2 to consider alternative biomass species. However, as discussed in Section 6.2, DRVT model is formulated to consider upstream biomass only. Process waste from plant is not integrated as potential alternative feedstock. In other words, the model does not see the process waste- gasification particle as a credible feedstock option for any of the technologies. Nevertheless, this concept can be interpreted via BECA model by assigning value of "0" in $TtoTfactor(m,j)$ for all process waste such that all technology will not consider process waste as a potential feedstock option.

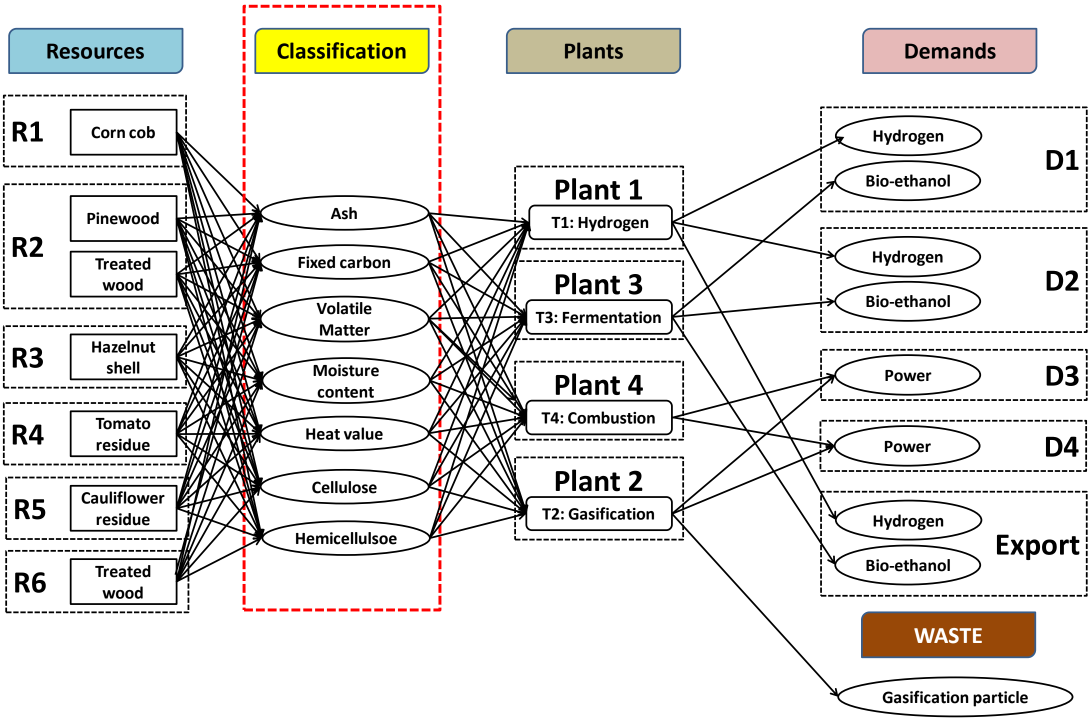


Figure 6- 14: Superstructure of biomass supply chain for DRVT approach

As discussed previously, the element acceptance range of both Technology 1 and Technology 2 are assumed to be within the element deviation factor, f_e of ±5 %; while the feedstock selection criteria for Technology 3 and Technology 4 are based on specific biomass properties. The upper and lower boundaries for both technologies are tabulated in Table 6-14. Similarly, simplified Equations 6-10, 6-11, and 6-17 are used as only one transportation mode is considered in this case study.

Table 6- 14: Biomass utilisation at respective resources point

Technology	Boundary	Biomass Element Characteristics (wt%)						
		Ash	FC	VM	MC	HV	Cell	Hcel
T1	Upper	3.1	18.3	76.3	7.4	20.2	31.5	15.8
	Lower	2.8	16.5	69.1	6.7	18.2	28.5	14.3
T2	Upper	1.7	20.0	75.2	8.4	22.3	42.0	21.0
	Lower	1.5	18.1	68.0	7.6	20.1	38.0	19.0
T3	Upper	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Lower	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T4	Upper	100.0	100.0	100.0	50.0	100.0	100.0	100.0
	Lower	0.0	0.0	0.0	0.0	0.0	0.0	0.0

6.3.2.3 Biomass Element Cycle Analysis model formulation

As discussed in the methodology, BECA model is an improved version of DRVT model by considering process waste as potential alternative feedstock. Figure 6-15 shows the superstructure of BECA approach.

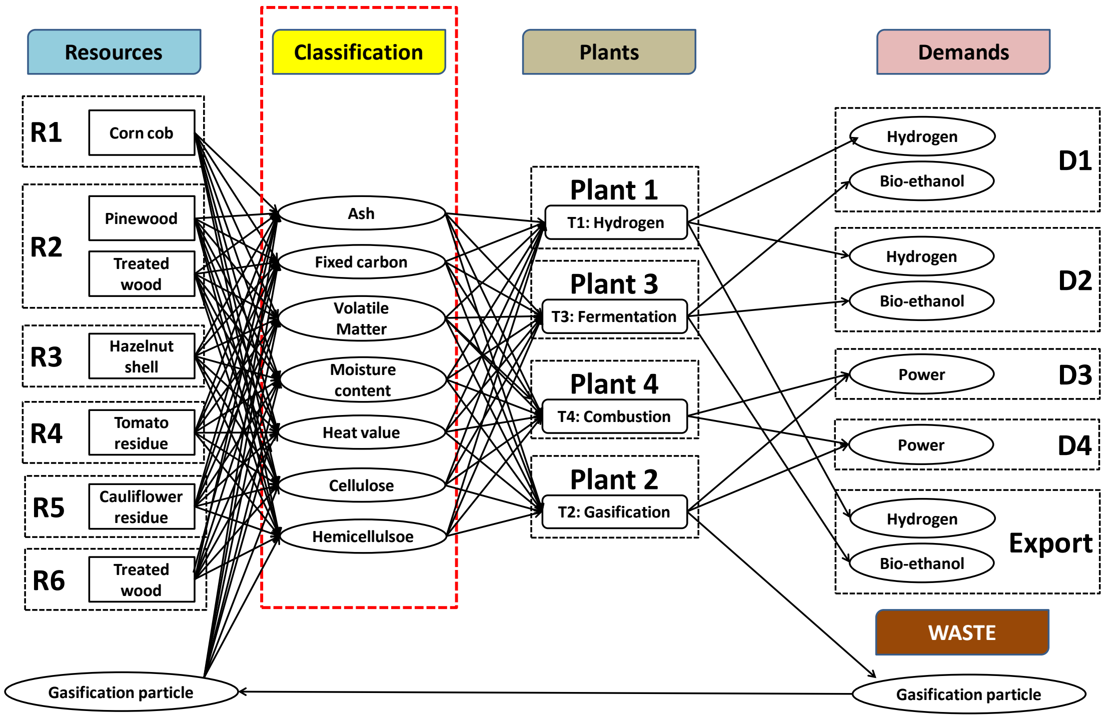


Figure 6- 15: Superstructure of biomass supply chain for BECA approach

Similar to DRVT model, BECA model suggests that feedstock selection is based on element acceptance range as stated in previous Table 6-14. Since this approach considered the recycle of process waste, all upstream biomass (corn cob, pine wood, hazelnut shell, treated wood, tomato residue, cauliflower residue) and process waste (gasification particle) are assigned with value of "1" in $TtoTfactor(m,j)$to allow the model to consider these material as potential recycle material. Transportation cost calculation also used the simplified Equations 6-10, 6-11 and 6-17 as only one mode of transportation is considered in this case study.

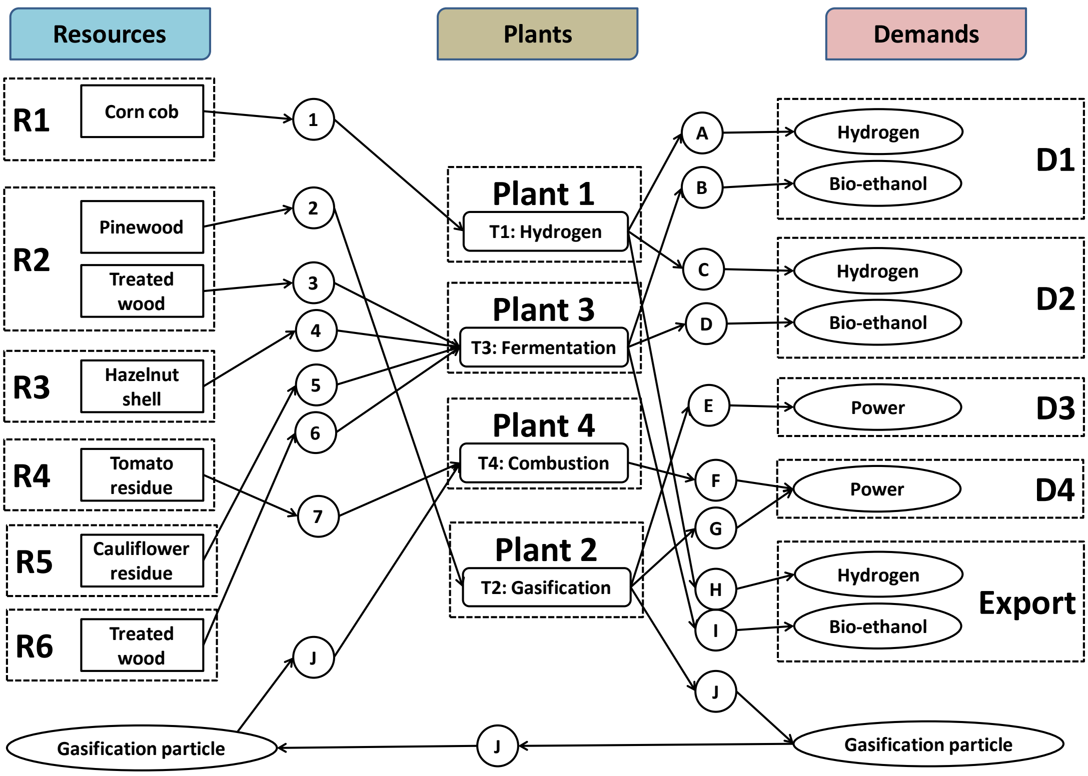
6.3.3 Model problem statement

The case studies were solved to maximise $\mathrm{Totalprofit}$ by using General Algebraic Modeling System (GAMS) software, version 23.4. The problem is solved via linear programming with CPLEX solver using Intel(r) Core(TM) i5-4200U CPU at 1.6 GHZ up to 2.30 GHz, 4 GB RAM memory and 64-bit Windows 8 system. The model consists of total of 26 blocks of equations and 22 blocks of variables. The model will propose the optimum solution for biomass distribution network from resources location to technology plants, technology plants to demand locations and recycle process waste (for BECA model). Appendix II presented GAMS coding and result for all the sub-cases.

6.3.4 Results and discussions

Figure 6-16 shows the optimum biomass supply chain network proposed by the conventional approach. Based on the result, feedstock for Technology 1 and Technology 2 consist of corn cob and pine wood respectively. Due to the limitation in alternative feedstock exploration in both technologies, the conventional biomass supply chain optimisation model only able to recognise the original biomass species as feedstock. However, Technology 3 and Technology 4 have co-related the process output with feedstock properties, thus, the model proposed combination of biomass feedstock for both process plant. Based on the result, the optimum feedstock ratio for Technology 3 consists of 72 wt% of treated wood, 11 wt% of tomato residue, and 18 wt% of cauliflower residue; while the feedstock ratio for Technology 4 consists of 99 wt% of treated wood and 1 wt% of gasification particle.

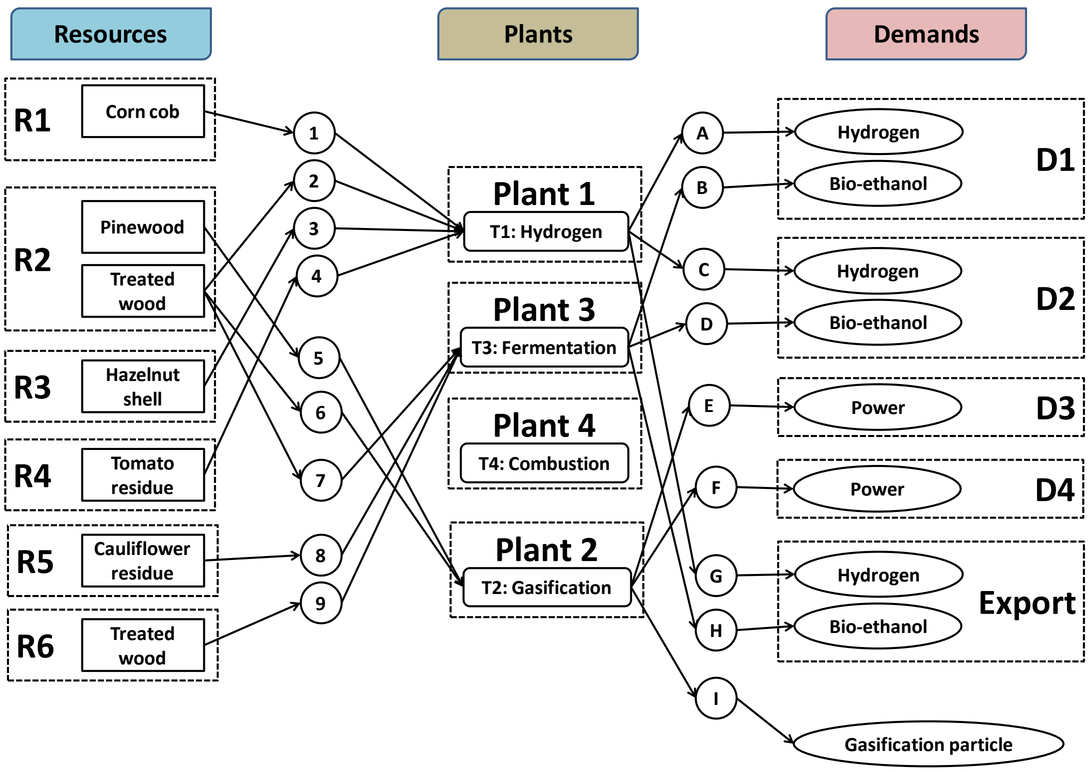
Nevertheless, this approach has shown the lack of flexibility in biomass feedstock selection in Technology 1 and Technology 2 resulting in biomass underutilisation within the system. The situation can be reflected in the current trend of biomass technology implementation where it is lack of researches in determining the acceptance capability of technology feedstock. Majority of biomass technology development focuses more in improving the technology by using alternative biomass species and altering the operating condition for optimum outcome. In addition, different location and system will have different species of biomass. This creates a huge gap to industrialised and generalised respective technology. Each technology needs to be tested with specific biomass species for implementation and not as much of work has been conducted such that the technology can be implemented in all systems. Nevertheless, feedstock selection via biomass element characteristics provides the platform to evaluate the resources based on properties instead of species. Sub-case studies B and C below show the advantages of element targeting approach in biomass supply chain management.



Indicator	1	2	3	4	5	6	7	A	B	C	D	E	F	G	H	I	J
Transported Material	3000 t	453 t	500 t	300 t	500 t	1500 t	950 t	5 t	15 t	20 t	13 t	50 GJ	55 GJ	15 GJ	66 t	271 t	5 t

Figure 6- 16: Optimum supply chain network for Case A- conventional approach

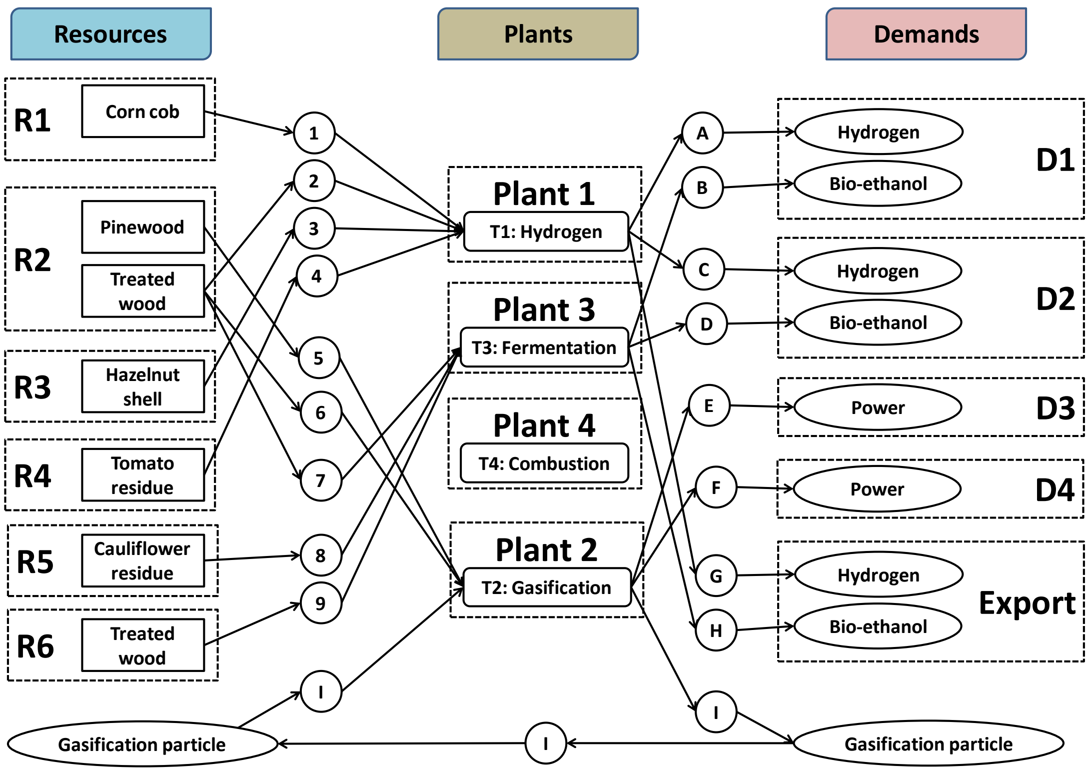
Figure 6-17 shows the optimum biomass supply chain network via DRVT approach. Using element targeting approach as feedstock selection platform, the model suggested combination of corn cob (69 wt%), treated wood (3 wt%), hazelnut shell (7 wt%), and tomato residue (22 wt%) as feedstock for Technology 1, and combination of pine wood (98 wt%) and treated wood (2 wt%) for Technology 2 to improve the overall system performance. Integration of multiple biomasses as feedstock also increases the total amount of feedstock availability for both Technology 1 and Technology 2 (as compared to sub-case study A). Hence, this enable higher production rate as long as it is within the process plant capability. Besides, the alternative biomasses have lower price thus increases the overall profit of the system. The model also suggested that the optimum feedstocks for Technology 3 are treated wood (79 wt%) and cauliflower residue (21 wt%); while Technology 4 is not feasible to operate. This may due to the relatively low conversion rate of the power plant as compared to Technology 2. As DRVT approach does not consider recycle loop for process waste, all the gasification particle generated are treated as waste.



Indicator	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	G	H	I
Transported Material	3000 t	117 t	300 t	950 t	814 t	20 t	363 t	1106 t	253 t	5 t	15 t	20 t	13 t	50 GJ	70 GJ	108 t	222 t	10 t

Figure 6- 17: Optimum supply chain network for Case B- DRVT approach

On the other hand, Case C proposed a different result as compared to Case B due to the improvement of recycle loop in BECA approach to reconsider utilisation of process waste. However, due to lack of information regarding the element characteristics of by-product and their generation rate, only one by-product (gasification particle from Technology 2) has the potential to be recycled in this case study. Thus only a small improvement in Case B is observed. The optimum supply chain network in Case C suggested that the feedstock ratio of Technology 1 remain the same as Case B. Nonetheless, optimum feedstock ratio for Technology 2 is 98.7 wt% of pine wood, 1.2 wt% of gasification particle (which is recycled from Technology 2 itself) and small amount of treated wood of 0.1 wt%. Feedstock ratio for Technology 3 is proposed to be 16 wt% of treated wood, 21 wt% of cauliflower residue, and 63 wt% of treated wood. Technology 4 is also not feasible to operate Case C due to low efficiency of combustion power plant which is not cost effective for the system. With the consideration of process waste, the model evaluated its potential as alternative resources, and suggested different optimum supply chain network.



Indicator	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	G	H	I
Transported Material	3000 t	117 t	300 t	950 t	814 t	0.6 t	382 t	500 t	1500 t	5 t	15 t	20 t	13 t	50 GJ	70 GJ	108 t	225 t	10 t

Figure 6- 18: Optimum supply chain network for Case C- BECA approach

In addition, the biomass resources utilisations in all three sub-cases are evaluated. Table 6-15 shows the utilisation amount and percentage for respective cases. The level of resources utilisation is very similar in all cases, with exception in pine wood from R2 and Technology 2 process waste, gasification particle. Case A shows the least utilisation of pine wood from R2 (18.9 wt%), this is mainly due to the specific feedstock selection criteria that based on biomass species for Technology 1 and Technology 2. In Cases B and C, more biomass utilisation is promoted in Technology 1, especially treated wood from R4, to increase the production rate and overall profit. This pushes the utilisation of pine wood in Technology 2 to fulfil the power demand. In Case A, treated wood is used as Technology 4 feedstock for power generation. The differences suggested that to achieve full potential of the system, utilisation of treated wood in Technology 1 is the better option as compared to use it in Technology 4.

Table 6- 15: Biomass utilisation at respective resources point

Location	Biomass species	A		B		C	
		t/d	Utilisation (wt%)	t/d	Utilisation (wt%)	t/d	Utilisation (wt%)
R1	Corn cob	3000.0	100.0	3000.0	100.0	3000.0	100.0
R2	Pinewood	453.4	18.9	813.7	33.9	817.9	34.1
	Treated wood	500	100.0	500.0	100.0	500.0	100.0
R3	Hazelnut shell	300	100.0	300.0	100.0	300.0	100.0
R4	Tomato residue	950	100.0	950.0	100.0	950.0	100.0
R5	Cauliflower residue	500	100.0	500.0	100.0	500.0	100.0
R6	Treated wood	1500	100.0	1,500.0	100.0	1,500.0	100.0
T2	Gasification particle	5.4	100.0	-	-	9.9	100.0

Table 6-16 shows the level of market demand achieved in each sub-cases. Generally all market demands are fulfilled in each case, with the differences in exportation. Element targeting approach provides a systematic feedstock selection platform for Technology 1 to produce more hydrogen to increase its exportation value from 66.4 t/d (Case A) to 108.0 t/d (Case B and Case C). In addition, recycle use of process waste in Case C increases the availability of biomass resources, thus enable higher production rate of bio-ethanol. In addition, Table 6-17 presents the total profit of the overall system. BECA approach has shown an improvement over DRVT approach and the conventional approach in this case study. Both DRVT and BECA models significantly improved the system by consideration of alternative feedstock for Technologies 1 and 2 via element targeting approach.

Table 6- 16: Market demand fulfilled

Location	**Product**	**A**		**B**		**C**	
		t/d	**Fulfil (wt%)**	**t/d**	**Fulfil (wt%)**	**t/d**	**Fulfil (wt%)**
Demand 1	Hydrogen	5	100	5	100	5	100
	Bio-ethanol	15	100	15	100	15	100
Demand 2	Hydrogen	20	100	20	100	20	100
	Bio-ethanol	13	1000	13	100	13	100
Demand 3	Power	50 GJ	100	50 GJ	100	50 GJ	100
Demand 4	Power	70 GJ	100	70 GJ	100	70 GJ	100
Export	Hydrogen	66.4	-	108.0	-	108.0	-
	Bio-ethanol	270.7	-	222.4	-	224.6	-

Table 6- 17: Total profit in respective cases

	Case		
	A	**B**	**C**
Total profit	$ 243.7k /d	$ 331.9k /d	$ 333.2k /d

With consideration of more underutilised biomass and process waste, the system will have more flexibility in supply chain network. Integration between multiple regional systems could also further optimise the overall biomass supply chain system.

However, noted that the proposed element acceptance range for Technology 3 and Technology 4 are based on limited literature input and has limited element constraint. This indicates that the technologies may be too flexible in accepting alternative biomasses which may not be feasible in real life. This further highlight the importance of experimental work that focus on construction of element acceptance range and identifying key elements to allow higher chances of biomass technology implementation. The study should also be expended to include elements that affecting enzyme or organic activity for complex organic reaction such as fermentation or mineral content that may result in catalytic reactions. For example, impact of mineral content and toxicity of biomass feedstock to fermentation, pyrolysis and gasification processes. In addition, the relation between biomass key elements and process outcome in similar technologies can also used as a guideline to improve current element acceptance range.

Nevertheless, the integration of biomass supply chain via element targeting as shown in BECA approach enhances the flexibility in biomass selection and biomass supply chain network and shown a better optimum result as compared to DRVT approach. This approach rectified current biomass industry problem such as biomass shortage or unavailability. With a proper element acceptance range, any biomass or biomass mixture can be used as alternative feedstock for respective technology provided the feedstock is within the element acceptance range. Thus, technology implementation is no longer subject to the availability of specific biomass species.

6.4 Sensitivity analysis: Application of element targeting approach in biomass supply chain fluctuation

Both Sections 6.2 and 6.3 have demonstrated the application of element targeting to incorporate underutilised biomasses and alternative biomasses into the existing supply chain distribution network. The main philosophy of element targeting approach is to enhance the flexibility of technology acceptance towards multiple biomass species, where the determining factors are the element characteristic instead of biomass species. By using this philosophy as the basis, the application of element targeting is not limited only to integration of underutilised biomass only.

Due to the enhanced flexibility in biomass feedstock selection, element targeting approach can also be implemented to deal with biomass fluctuation scenarios, such as the dynamic nature of biomass resources supply. Two major fluctuations in biomass supply are, i) fluctuation in biomass properties and ii) fluctuation in biomass quantity. The fluctuation in biomass properties is a very common problem. Factors such as the weather, harvesting efficiency, storage period, delay of shipment, seasons, handling, and growth of bacterial have the potential to impact the feedstock properties. Nevertheless, discussions of DRVT and BECA approach in previous sections have shown a solid example on dealing with various biomasses with unique properties. The approaches suggested that mixing of biomasses is an alternative solution to ensure consistency of feedstock properties. Both models will determine the best biomass ratio to ensure the feedstock is within acceptance range. Thus, using the same concept, sufficient discussion on the application of element targeting approach to tackle the fluctuation of resources properties in biomass supply chain network is provided in the previous sections.

This section will focus on the discussion of implementation of element targeting approach to target the issue of biomass quantity variation. Fluctuation of biomass quantity can be due to several reasons, such as seasonal biomass, harvesting issues, market competition, and logistic delay. Higher biomass generation rate will cause more biomass waste, but many biomasses can be disposed on site (especially at plantation site) for nutrient regeneration. On the other hand, shortage of biomass will have more significant impact to the supply chain management. Conventionally, the counter measure is to import the resources from other region. This will greatly impact the cost of raw material and total profit due to the additional expenses on transportation and import duties. Resource backup at storage as a buffer point is another alternative solution. However, it raised another issue in storage management (such as bacteria growth) to ensure biomass quality. Thus, an alternative counter measure is required to handle the issue of raw material availability issue. Utilising element targeting philosophy, fluctuation of biomass quantity can be rectified by replacing the original biomass feedstock with alternative biomass without compromising the process performance. A demonstration case study is conducted. This case study implements DRVT approach in a regional area to optimise biomass supply chain network through inconsistency of biomass supply.

6.4.1 Case study of element targeting approach application in biomass supply fluctuation

The same biomass regional system from Section 6.2 is used to demonstrate the applicability of element targeting in solving biomass supply availability fluctuation. Thus, the mapping of the system can refer to Figure 6-1 in previous section. The information of average biomass availability and market demand, process technologies in respective plants, biomass element characteristics properties and element acceptance range for each technology remained unchanged, which summarised in Table 6-1, Table 6-2, Table 6-3 and Figure 6-2. Similarly, only one mode of transportation is considered in this case study. However, four different scenarios of biomass shortage are evaluated in this section and are described in Table 6-18. This is to demonstrate the model capability to tackle resources fluctuation and to suggest optimum supply chain network in different scenario.

Table 6- 18: Biomass resources fluctuation scenarios

Case Study	Description of biomass resources fluctuation
(i)	All biomass availability fulfilled standard average requirement
(ii)	R1 generate 50% less than standard average amount for each biomass
(iii)	R2 generate 50% less than standard average amount for each biomass
(iv)	Both R1 and R2 generate 50% less than standard average amount for each biomass

DRVT model is used in this case study as the integration approach to optimise the fluctuation problem. General methodology and mathematical model description can refer to Section 6.2.1, and model formulation and results are presented in Appendix III. Table 6-19 tabulated the resources availability in each sub-cases. This is the only difference between the sub-cases to allow the comparison of the optimum supply chain network during resources fluctuation. All cases were solved to maximise $\mathrm{Totalprofit}$ by using General Algebraic Modeling System (GAMS) software, version 23.4. The problem is solve via linear programming with CPLEX solver using Intel(r) Core(TM) i5-4200U CPU at 1.6 GHZ up to 2.30 GHz, 4 GB RAM memory and 64-bit Windows 8 system.

Table 6- 19: Information on resources fluctuation

Location	Biomass	Availability (t/day)			
		Case (i)	Case (ii)	Case (Iiii)	Case (iv)
R1	Palm shell (PS)	2500	1250	2500	1250
	Oil palm fronds (OPF)	1500	750	1500	750
	Palm oil EFB	2000	1000	2000	1000
	Palm kernel trunk (PKT)	800	400	800	400
R2	Palm shell (PS)	1750	1750	875	875
	Oil palm fronds (OPF)	2300	2300	1150	1150
	Palm oil EFB	2100	2100	1050	1050
	Palm Mesocarp Fibre (PMF)	750	750	375	375
R3	Soft wood (SW)	1500	1500	1500	1500
R4	Hard wood (HW)	1750	1750	1750	1750

6.4.2 Results and discussions

All cases of fluctuation in biomass availability to reflect the dynamic condition in biomass supply chain management is optimised via DRVT approach. The model provides optimum biomass selection and distribution network to maximise the overall profit of the regional system. As the main focus of the study is to evaluate the functionality of element targeting approach to handle biomass resources fluctuation, other parameters such as location data, plant capacity, market demand, and transportation cost are set to be constant. Thus, the amount of product send to local market demand is remained constant in all four cases. This also leads to the constant distribution network between process plant and market demand due to the constant location between process plant and local market location. Table 6-20 tabulated the distribution network of product from each process technology to local market demand, which is the same for all sub-cases. Nevertheless, the amount of product (syngas from Plant 3) exported to other region is impacted due to fluctuation in total raw material availability, where Case (i) exported 11800 Nm^3; Case (ii) exported 9002 Nm^3; Case (iii) exported 7724 Nm^3; and Case (iv) exported 5279 Nm^3.

Table 6- 20: Biomass resources fluctuation scenarios

Product delivered to local demand		D1	D2	D3
Plant 1	T1: Bio-oil (t)	1000	-	-
Plant 2	T2: Syngas (Nm^3)	-	600	350
	T3: Power (MJ)	-	-	700
Plant 3	T2: Syngas (Nm^3)	-	-	-
Plant 4	T4: Bio-ethanol (t)	850	-	-

In addition, due to the fluctuation of biomass availability, the optimum distribution network between resource points and process plants are affected. Thus, the overall raw biomass cost and transportation cost are also subject to changes. Element targeting approach enables the model to determine optimum biomass selection based on the element acceptance range of each technology and element characteristics of each biomass species. Biomass with lower raw material cost and transportation cost (nearer to process plant) are more favourable to maximise the overall profit. Thus the differences between the four case studies are mainly in the distribution network between biomass resources location and process plants, and the maximum feasible amount of product generated for exportation. Table 6-20 shows the distribution of biomass from resources points to each process plants for all Case (i), Case (ii), Case (iii), and Case (iv). The overall profits of each case are reported to be RM 808k, RM 602k, RM 339k, and RM 110k respectively. Overall profit of Case D is the lowest among all cases due to the least biomass availability in the system, thus limits the production for exportation.

The model optimised the system by suggesting alternative biomass supply chain network and feedstock ratio to handle each scenario. For example, R1 provides 89 % of biomass feedstock (palm shell and EFB) for Technology 1 at Plant 1 in Case (i). Due to unforeseen circumstances where R1 generates 50 % less biomass as described in Case (ii), an alternative solution is proposed to utilise the same biomass species of palm shell from R2 as substitution. It is interesting to note that the overall biomass species ratio is remained constant as shown in Figure 6-19. This is due to availability of palm shell in R2 which is sufficient to operate as backup resource. However, in the case where R2 generate less biomass, Case (iii) and Case (iv), palm kernel trunk from R1 is used as an alternative feedstock for

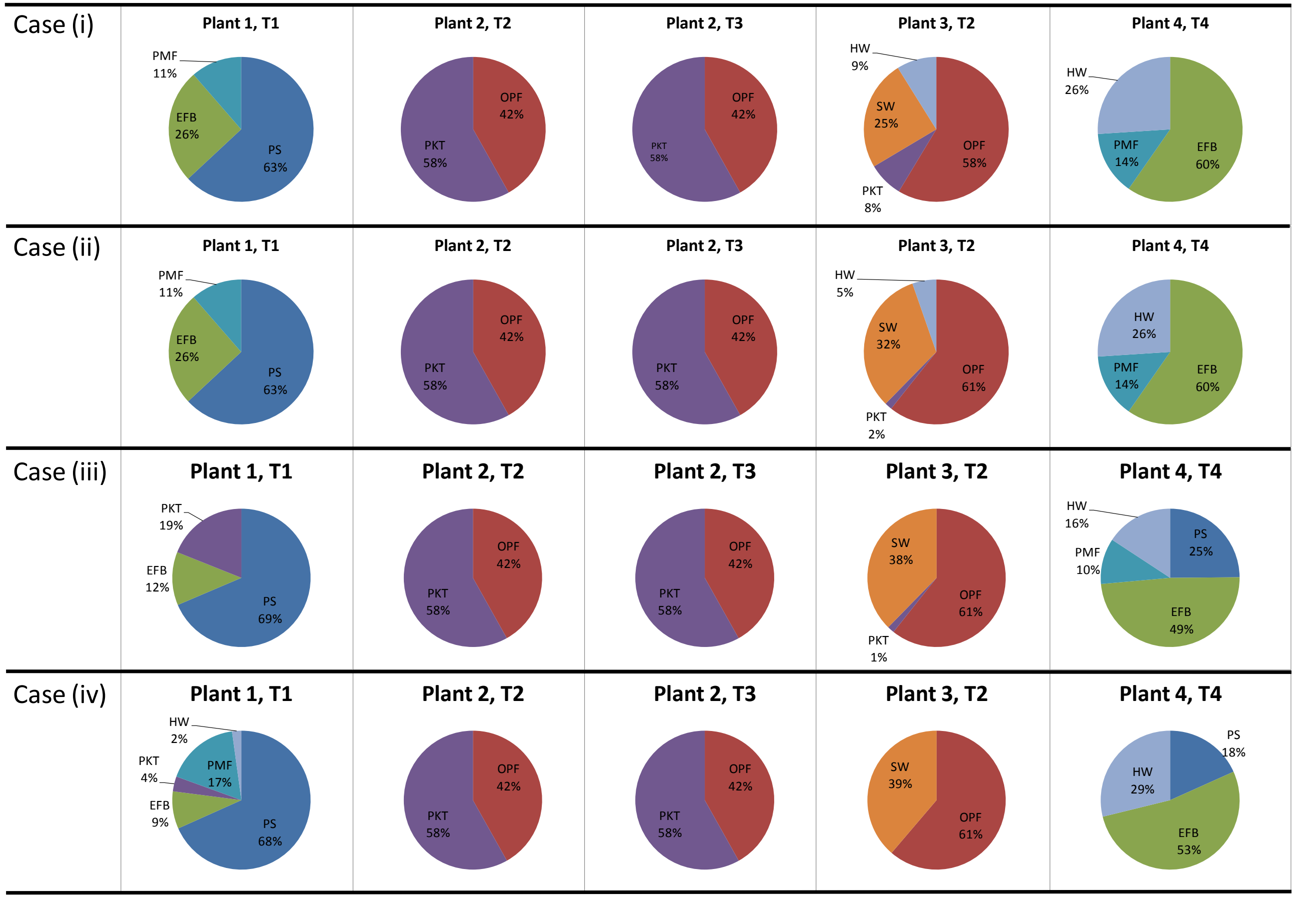
Table 6- 21: Biomass resources fluctuation scenarios

Biomass delivered to process plant (t)		Case (i)					Case (ii)				
		Plant 1, T1	Plant 2, T2	Plant 2, T3	Plant 3, T2	Plant 4, T4	Plant 1, T1	Plant 2, T2	Plant 2, T3	Plant 3, T2	Plant 4, T4
R1	PS	1367.81	-	-	-	-	1250.00	-	-	-	-
	OPF	-	204.99	28.45	1266.56	-	-	204.99	28.45	516.56	-
	EFB	554.15	-	-	-	-	554.15	-	-	-	-
	PKT	-	284.70	39.51	475.78	-	-	284.70	39.51	75.78	-
R2	PS	-	-	-	-	-	117.81	-	-	-	-
	OPF	-	-	-	2300.00	-	-	-	-	2300.00	-
	EFB	-	-	-	-	2100.00	-	-	-	-	2100.00
	PMF	247.23	-	-	-	502.77	247.23	-	-	-	502.77
R3	SW	-	-	-	1500.00	-	-	-	-	1500.00	-
R4	HW	-	-	-	540.51	915.45	-	-	-	248.10	915.45

Biomass delivered to process plant (t)		Case (iii)					Case (iv)				
		Plant 1, T1	Plant 2, T2	Plant 2, T3	Plant 3, T2	Plant 4, T4	Plant 1, T1	Plant 2, T2	Plant 2, T3	Plant 3, T2	Plant 4, T4
R1	PS	1487.95	-	-	-	-	1250.00	-	-	-	-
	OPF	-	204.99	28.45	1266.56	-	-	204.99	28.45	516.56	-
	EFB	270.13	-	-	-	308.45	189.72	-	-	-	810.28
	PKT	411.11	284.70	39.51	64.67	-	75.78	284.70	39.51	-	-
R2	PS	-	-	-	-	1651.67	231.58	-	-	-	643.43
	OPF	-	-	-	1150.00	-	-	-	-	1150.00	-
	EFB	-	-	-	-	1050.00	-	-	-	-	1050.00
	PMF	-	-	-	-	375.00	375.00	-	-	-	-
R3	SW	-	-	-	1500.00	-	-	-	-	1054.79	-
R4	HW	-	-	-	-	133.09	47.12	-	-	-	1014.50

Plant 1 due to limited palm mesocarp fibre in R2. As both resources from R1 and R2 are affected in Case (iv), Plant 1 utilised multiple biomass species from multiple resource locations to provide sufficient raw material that fulfilled the element acceptance range of the technology. The result shows that the integration of biomass via element characteristic enabled flexibility in biomass selection to ensure consistence production rate to fulfilled market demand. The model guarantees biomass feedstock is within element acceptance range of respective technology to ensure consistency in process operation. Similar result is obtained when comparing the biomass feedstock ratio of Technology 4 in Plant 4 in Case (iv) with respect to other cases. Due to the limitation of biomass from R1 and R2, hard wood is utilised as alternative biomass feedstock to replace palm mesocarp fibre.

Based on the result presented, it shows that the element targeting act as a platform to evaluate the status of biomass availability and to propose an optimum supply chain network in order to achieve the objective function. This provides opportunity for management to determine the best solution in critical event of fluctuation in biomass availability. The method can be implemented for fluctuation of market demand, fluctuation of element acceptance range of process technology due to process modification, changes of biomass collection point, introduction of new biomass species or resources, and fluctuation of biomass quality in terms of different value of element characteristics. Nevertheless, the applicability of element targeting approach is still subject to the regional biomass system condition. On the other hand, more element characteristics of biomass can be considered in future work to ensure consistency in process operation.



Legend:
PS: palm shell; **OPF**: oil palm frond; **EFB**: palm oil empty fruit bunch; **PKT**: palm kernel trunk; **PMF**: palm mesocarp fiber; **SW**: soft wood; **HW**: hard wood

Figure 6- 19: Optimum biomass feedstock ratio for each process technology in each case

6.5 Conclusions

This chapter has well demonstrated the implementation of element targeting approach into biomass supply chain optimisation model. The advantages and differences between the state-of-the-art integration approach and conventional approach are discussed via supply chain superstructures and case studies. The first case study showed that DRVT approach enables the model to consider underutilised biomasses as alternative process feedstock to reduce the raw material and transportation cost. Second case study proposed another modelling approach, BECA which further improves the DRVT approach by incorporate process waste/by-product into consideration as alternative resource. This approach includes the study of potential of utilisation of resources from each process stage. A recycle loop is created within the model to reutilise the process waste and the result has shown an improvement over DRVT approach in the case study. The final case study demonstrated the application of element targeting approach in biomass supply chain management to solve the fluctuation problems in biomass supply. This sensitive analysis proposed that the element targeting is able to provide the optimum supply chain network based on the fluctuation of biomass availability.

From the discussion, the introduction of element targeting into conventional biomass supply chain optimisation model is undoubtedly improved the existing system. Conventional integration approaches restrict the process technology to select specific biomass species, thus many potential biomass species were not integrated into the system for consideration, leading to infeasible of biomass industry implementation in many region. With the introduction of element targeting, all biomass including underutilised biomass are used at their full potential. Flexibility of technology feedstock is improved without process modification to break through the conventional feedstock selection method based on biomass species. The case studies have shown that by integrating underutilised biomass via element characteristics is able to improve the current system and the overall total profit without process modification or introduction of new technology. Nevertheless, it is important to highlight that the success of integrating underutilised biomass is depending on the individual biomass regional system. There is a possibility that a regional biomass system where utilising alternative biomasses are infeasible, which could potentially due to low availability, far location, difficulty in collection and significant differences in properties. Nonetheless, element targeting approach provides a system evaluation platform to consider potential application of those resources. In conclusion, implementation of element targeting approach into existing conventional supply chain optimisation model enable a potential great improvement to the current biomass system.

Chapter 7:
CONCLUSIONS AND FUTURE WORKS

7.1 Conclusions

This thesis has illustrated a state-of-the-art philosophy for biomass integration in supply chain optimisation model. Upon the detailed literature review, several recommendations to fill in the gaps of current biomass supply chain network optimisation are proposed and discussed in Chapter 2. Based on the review, underutilisation of biomass is one of the main factors that restrict the full potential of biomass industry and its implementation. On the other hand, research has conducted to shows that the biomass technology performance has strong relation with feedstock element characteristics instead of biomass species. Thus, an innovative concept of element targeting approach is proposed in Chapter 3 to integrate the underutilised biomass into the existing biomass supply chain network via element characteristics. As the core philosophy of this research, element targeting approach transforms the limitation of the current system (which is underutilisation of biomass) into advantage of the improved supply chain network. Widely available and lower cost of underutilised biomass integrates into the system as alternative resources increases the flexibility of supply chain distribution network and further optimises the overall system.

Due to the novelty of the concept, concept verification is conducted to ensure applicability of the philosophy in real life scenario. Chapter 4 discussed the implementation of element targeting based on literature data. The results showed that it is possible to implement the approach into the technologies available in literature. In order words, the approach has proven to be feasible to implement into existing technologies. This is the most important advantage as the proposed element targeting approach can be implemented without major modification to the existing process and technology, which greatly minimises the modification and construction cost of equipment and process. Nevertheless, limitation and uncertainties of information within literature may result in inaccuracy of the verification. In order to ensure the feasibility of the approach, element targeting is again verified in Chapter 5, in this case via experimental work. Biomass mixture properties prediction based on linear relation of mass ratio is proven to be within the acceptable range. The concept of element acceptance range, which is the determining factor of technology flexibility in element targeting integration is analysed via biomass pyrolysis. The research has again showed promising result that the biomass technology performances are highly based on feedstock element characteristics and construction of element acceptance range is possible to allow process output prediction.

Upon verification of the concept, element targeting is integrated into biomass supply chain optimisation model. Chapter 6 discussed two models, Demand-Resources Value Targeting (DRVT) and Biomass Element Cycle Analysis (BECA), which both have shown a great improvement over the conventional biomass integration approach. The main improvement over the conventional approach is found to be the enhanced flexibility of integrating alternative and multiple biomasses into process technology. Based on the results, underutilised biomasses are considered within the supply chain network and are utilised as valuable feedstock. This further improves the overall system by minimising the biomass waste and waste management cost. Another case study has been conducted and the results showed that the element targeting approach is also able to deal with the fluctuation problem of biomass supply. The approach optimises the biomass distribution network by replacing the biomass shortage with alternative biomass as the solution for fluctuation of biomass availability.

In conclusion, intensive research has been conducted on current biomass supply chain and a novel integration approach, element targeting approach is introduced. This thesis covers the overall process from analysing the research gaps, introduction of novel concept, verification of concept, and demonstration of applications. Element targeting approach has proven to be a systematic and well developed integration platform to improve the existing conventional biomass supply chain distribution network management and optimisation model. This approach provides a systematic platform via biomass element characteristics and technology element acceptance range to diversify the technology feedstock selection and biomass applications. The proposed models show higher level of supply chain integration with improved flexibility without major process modification.

7.2 Future works

As discussed above, intensive research has been conducted to improve the existing biomass supply chain integration and optimisation model via the novel element targeting approach. All three objectives stated in the beginning of research (Section 1.3) have fulfilled. The scope of work has covers the relevant topics to ensure the applicability of the new concept. Nevertheless, much improvement of element targeting can be expected. This also creates a sustainable research chain for continuity of research that aim for a better solution to achieve sustainability. Few potential future works were identified and can be separated into two research fields.

7.2.1 Future works in biomass process technology development

The first part of future work focus on the implementation of element targeting approach into development of biomass process technology. The scope will focus more on laboratory experiment to construct element acceptance range for respective technology. According to this research, study on the element acceptance range is a very critical step to enable integration of multiple biomasses. The conventional development of biomass technology has rarely explored the flexibility of feedstock tolerances. This research gaps normally leads to difficulty to implement well developed technology in other region that do not have the specific biomass species. This research work has only conducted the verification of element acceptance range on biomass pyrolysis due to resource and time constraints. Nevertheless, the following are some of the potential work as the research continuity:

I. Expansion of biomass properties integration research to consider non-mass fraction conversed properties, such as biomass pH value, thermal conductivity, density, and etc. These properties have the potential to be the key elements for certain biomass technologies. Thus further analysis and verification into this scope of work will provide a good biomass properties estimation platform to allow more biomass properties to be considered in the biomass selection platform and element targeting approach.

II. Conduct element acceptance range analysis on other biomass process such as fermentation, gasification, and combustion. This research can applied on process technology that has substantial development, where the optimum operating conditions are determined. Construction of element acceptance range will help to increase the value of respective technology due to increase potential of implementation in various regions instead of limiting to area with specific biomass feedstock. Besides, construction of element acceptance range is strategized at later stage of experiment to minimise the research cost where only the optimum operating conditions is used.

III. Increase biomass species variety to study wider range of feedstock element characteristics. This will allow the technology to be tested on bigger feedstock fluctuation and hence to strengthen the proposed element acceptance range.

IV. Consideration of pretreatment process to study their impact to element acceptance range. For example, high feedstock moisture content can be rectified via drying process provided that it is economically feasible.

V. Integration of process condition with element acceptance range. The idea of this potential research scope is to analyse the impact of each process conditions to the element acceptance range of respective technology. The process conditions to be considered are feedstock size, flowrate, temperature, pressure, equipment setup, and catalytic reaction. These will create multi-dimensions radar chart or a co-relation with respective to element characteristics and operating conditions.

7.2.2 Future works in biomass supply chain optimisation development

Another potential future work for this research is the expansion of the proposed mathematical models. At the moment, DRVT and BECA approach only consider the main factors in biomass supply chain, namely the location factor, raw material cost, operating cost, transportation cost and market demand. More variables in supply chain network management can be integrated in parallel with element targeting approach.

I. Enhance the model by consideration of centralised and de-centralised approach, storage point consideration, and scheduling. This will create a more robust model to be implemented in real life industry scenarios.
II. Inclusion of Geographical Information System to reflect the road and traffic conditions. These inputs are also a critical factor to determine the optimum distribution network. Live time information and prediction capability will further strengthen the future model application.
III. Consideration of uncertainty cases in resources availability and quality, logistic issue, process upset, and market fluctuation. No doubt that biomass industry is always in a dynamic state with many unforeseen scenarios. Thus the optimisation model can be improved to handle those unexpected variation and offers a better decision making tool.

The proposed future works in two different research fields based on the concept of element targeting is expected to improve the current research and development to have wider applications in real life. This research has produced high value information for the beneficial of current biomass process technology and supply chain management, as well as the research continuity for future development.

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APPENDIX I

Case study 1A

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*Model formulation for sub-case study 1A

set
i resources /R1, R2, R3, R4/
j technology /1_T1, 2_T2, 2_T3, 3_T2, 4_T4/
k demand /D1, D2, D3, Export/
m material /PS, OPF, EFB, PKT, PMF, SW, HW, BO, BE, SG, PW/
e element /Cel, Hcel, Lig, Ext, Ash, MC/

alias (j,jp) ;

Positive variables
RtoT(i,m,j), TtoT(jp,m,j), TtoD(jp,m,k);

Positive Variables
MatRecT(m,j), TMatRecT(j), MatGenT(m,jp), Zz(j) ;

* MASS

* resources availability
Table resource(i,m)
         PS      OPF     EFB     PKT     PMF     SW      HW      BO
BE      SG      PW
R1       2500    1500    2000    0       0       0       0       0
0       0       0
R2       1750    2300    2100    0       0       0       0       0
0       0       0
R3       0       0       0       0       0       0       0       0
0       0       0
R4       0       0       0       0       0       0       0       0
0       0       0;


* technology conversion
Table yield1_T1(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0.461   0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0;

Table yield2_T2(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
```

```
PKT      0        0        0        0        0
PMF      0        0        0        0        0
SW       0        0        0        0        0
HW       0        0        0        0        0
BO       0        1.94     0        0        0
BE       0        0        0        0        0
SG       0        0        0        0        0
PW       0        0        0        0        0;

Table yield2_T3(m,jp)
         1_T1     2_T2     2_T3     3_T2     4_T4
PS       0        0        0        0        0
OPF      0        0        0        0        0
EFB      0        0        0        0        0
PKT      0        0        0        0        0
PMF      0        0        0        0        0
SW       0        0        0        0        0
HW       0        0        0        0        0
BO       0        0        0        0        0
BE       0        0        0        0        0
SG       0        0        0        0        0
PW       0        0        10.30    0        0;

Table yield3_T2(m,jp)
         1_T1     2_T2     2_T3     3_T2     4_T4
PS       0        0        0        0        0
OPF      0        0        0        0        0
EFB      0        0        0        0        0
PKT      0        0        0        0        0
PMF      0        0        0        0        0
SW       0        0        0        0        0
HW       0        0        0        0        0
BO       0        0        0        0        0
BE       0        0        0        0        0
SG       0        0        0        10.3     0
PW       0        0        0        0        0;

Table yield4_T4(m,jp)
         1_T1     2_T2     2_T3     3_T2     4_T4
PS       0        0        0        0        0
OPF      0        0        0        0        0
EFB      0        0        0        0        0
PKT      0        0        0        0        0
PMF      0        0        0        0        0
SW       0        0        0        0        0
HW       0        0        0        0        0
BO       0        0        0        0        0
BE       0        0        0        0        0.2416
SG       0        0        0        0        0
PW       0        0        0        0        0;

* demand constraint
Table demand_upper(m,k)
         D1       D2       D3       Export
PS       0        0        0        0
OPF      0        0        0        0
EFB      0        0        0        0
PKT      0        0        0        0
PMF      0        0        0        0
SW       0        0        0        0
HW       0        0        0        0
```

```
BO       1600    0       0       0
BE       1550    0       0       0
SG       0       860     350     0
PW       0       0       1200    0         ;

Table demand_lower(m,k)
         D1      D2      D3      Export
PS       0       0       0       0
OPF      0       0       0       0
EFB      0       0       0       0
PKT      0       0       0       0
PMF      0       0       0       0
SW       0       0       0       0
HW       0       0       0       0
BO       1600    0       0       0
BE       1550    0       0       0
SG       0       860     350     0
PW       0       0       1200    0         ;

* Biomass recycle contraint factor (no product is being recycle)
Table TtoTfactor(m,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       1       1       1       1       1
OPF      1       1       1       1       1
EFB      1       1       1       1       1
PKT      1       1       1       1       1
PMF      1       1       1       1       1
SW       1       1       1       1       1
HW       1       1       1       1       1
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0   ;


Equation
E1(i,m), E2(m,j), E3(m,jp), E4(m,jp), E5(m,k), E5b(m,k), E2b(j);

* Resources constraint
E1(i,m).. sum((j), RtoT(i,m,j))=l=resource(i,m);

* Total material received at T
E2(m,j)..
sum((i),RtoT(i,m,j))+(sum((jp),TtoT(jp,m,j))*TtoTfactor(m,j))=e=MatRe
cT(m,j);

E2b(j)..         sum((m),(MatRecT(m,j)))=e=TMatRecT(j);


* ELEMENT
Table element(m,e)
         Cel     Hcel    Lig     Ext     Ash     MC
PS       0.277   0.216   0.440   0.02    0.021   0.11
OPF      0.304   0.404   0.217   0.027   0.013   0.16
EFB      0.373   0.146   0.317   0.013   0.067   0.10
PKT      0       0       0       0       0       0
PMF      0       0       0       0       0       0
SW       0       0       0       0       0       0
HW       0       0       0       0       0       0
BO       0       0       0       0       0       0
BE       0       0       0       0       0       0
```

```
SG       0       0       0       0       0       0
PW       0       0       0       0       0       0        ;

Table e_upper(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.327   0.354   0.354   0.354   0.423
Hcel     0.266   0.454   0.454   0.454   0.196
Lig      0.49    0.267   0.267   0.267   0.367
Ext      0.07    0.077   0.077   0.077   0.063
Ash      0.071   0.063   0.063   0.063   0.117
MC       0.16    0.21    0.21    0.21    0.15   ;

Table e_lower(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.227   0.254   0.254   0.254   0.323
Hcel     0.166   0.354   0.354   0.354   0.096
Lig      0.39    0.167   0.167   0.167   0.267
Ext      0       0       0       0       0
Ash      0       0       0       0       0.017
MC       0.06    0.11    0.11    0.11    0.05        ;


Positive Variable
EleRecT(m,e,j),Z3b(e,j);

Equation
E6(m,e,j), E6b(e,j), E7(e,j), E8(e,j);

* Element received at T
E6(m,e,j).. MatRecT(m,j)*element(m,e)=e=EleRecT(m,e,j) ;

* Sum of element (tonne) at T
E6b(e,j)..  sum((m),EleRecT(m,e,j))=e=Z3b(e,j);

E7(e,j).. sum((m),EleRecT(m,e,j))=l=e_upper(e,j)*TMatRecT(j);
E8(e,j).. sum((m),EleRecT(m,e,j))=g=e_lower(e,j)*TMatRecT(j);

*ELEMENT end


*MASS cont..


*Total material product at T
E3(m,jp).. TMatRecT('1_T1')*yield1_T1(m,jp) +
TMatRecT('2_T2')*yield2_T2(m,jp) + TMatRecT('2_T3')*yield2_T3(m,jp) +
TMatRecT('3_T2')*yield3_T2(m,jp) +
TMatRecT('4_T4')*yield4_T4(m,jp)=e=MatGenT(m,jp);



* Product constraint
E4(m,jp)..
(sum((k),TtoD(jp,m,k))+sum((j),TtoT(jp,m,j)))=l=MatGenT(m,jp);

* Demand constraint
E5(m,k).. sum((jp),TtoD(jp,m,k))=l=demand_upper(m,k);
E5b(m,k).. sum((jp),TtoD(jp,m,k))=g=demand_lower(m,k);


* MASS end
```

```
* Transportation
Parameter
transcost transportation cost RM per tonne per km / 0.5 /;

Positive Variables
Cost_RtoT(i,j), Cost_TtoT(j,jp), Cost_TtoD(jp,k), Ttranscost;

Table distance_RtoT(i,j)
         1_T1     2_T2     2_T3     3_T2     4_T4
R1       600.0    360.6    360.6    854.4    565.7
R2       608.3    583.1    583.1    447.2    360.6
R3       1063.0   583.1    583.1    400.0    640.3
R4       721.1    223.6    223.6    500.0    400.0     ;

Table distance_TtoT(j,jp)
         1_T1     2_T2     2_T3     3_T2     4_T4
1_T1     0        500.0    500.0    584.4    447.2
2_T2     500.0    0        0        509.9    223.6
2_T3     500.0    0        0        509.9    223.6
3_T2     854.4    509.9    509.0    0        412.3
4_T4     447.2    223.6    223.6    412.3    0     ;

Table distance_TtoD(jp,k)
         D1       D2       D3       Export
1_T1     640.3    300.0    500.0    905.5
2_T2     200.0    400.0    0        781.0
2_T3     200.0    400.0    0        781.0
3_T2     316.2    583.1    509.9    412.3
4_T4     223.6    223.6    223.6    583.1  ;

Equations
E9(i,j), E10(j,jp), E11(jp,k), E12;

E9(i,j)..
(sum((m),RtoT(i,m,j))*distance_RtoT(i,j)*transcost)=e=Cost_RtoT(i,j);
E10(j,jp)..
(sum((m),TtoT(j,m,jp))*distance_TtoT(j,jp)*transcost)=e=Cost_TtoT(j,j
p);
E11(jp,k)..
(sum((m),TtoD(jp,m,k))*distance_TtoD(jp,k)*transcost)=e=Cost_TtoD(jp,
k);
E12..
(sum((i,j),Cost_RtoT(i,j)))+(sum((j,jp),Cost_TtoT(j,jp)))+(sum((jp,k)
,Cost_TtoD(jp,k)))=e=Ttranscost;

* TRANSPORTATION end


* Profit
Parameter
value(m) selling value /PS 120, OPF 110, EFB 105, PKT 65, PMF 75, SW
50, HW 85, BO 300, BE 450, SG 325, PW 260/;

Positive Variable
Z7(m),Z7b, Z8(m), Z9(m),Z9b, profit;

Variable
totalprofit;
```

```
Equation
E13(m),E13b, E15(m),E15b, E16, obj  ;

* Total resources used in R
E13(m).. sum((i,j),RtoT(i,m,j))=e=Z7(m);

* Total amount used in purchasing raw material
E13b.. sum((m),((Z7(m))*value(m)))=e=Z7b;

* Total product send to D
E15(m).. sum((jp,k),TtoD(jp,m,k))=e=Z9(m);

* Total sell in D
E15b.. sum((m),((Z9(m))*value(m)))=e=Z9b;

E16.. Z9b-Z7b=e=profit;
obj.. Totalprofit=e=profit-Ttranscost ;


Model MarkII /all/;

Solve MarkII using LP maximising Totalprofit;

display RtoT.l, TtoT.l, TtoD.l;
```

Case study 1B

```
*Model formulation for sub-case study 1B

set
i resources /R1, R2, R3, R4/
j technology /1_T1, 2_T2, 2_T3, 3_T2, 4_T4/
k demand /D1, D2, D3, Export/
m material /PS, OPF, EFB, PKT, PMF, SW, HW, BO, BE, SG, PW/
e element /Cel, Hcel, Lig, Ext, Ash, MC/

alias (j,jp) ;

Positive variables
RtoT(i,m,j), TtoT(jp,m,j), TtoD(jp,m,k);

Positive Variables
MatRecT(m,j), TMatRecT(j), MatGenT(m,jp), Zz(j) ;

* MASS

* resources availability
Table resource(i,m)
         PS      OPF     EFB     PKT     PMF     SW      HW      BO
BE      SG      PW
R1       2500    1500    2000    800     0       0       0       0
0       0       0
R2       1750    2300    2100    0       750     0       0       0
0       0       0
R3       0       0       0       0       0       1500    0       0
0       0       0
R4       0       0       0       0       0       0       1750    0
0       0       0;

* technology conversion
Table yield1_T1(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0.461   0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0;

Table yield2_T2(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       1.94    0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
```

```
PW       0       0       0       0       0;

Table yield2_T3(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       10.30   0       0;

Table yield3_T2(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       10.3    0
PW       0       0       0       0       0;

Table yield4_T4(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0.2416
SG       0       0       0       0       0
PW       0       0       0       0       0;

* demand constraint
Table demand_upper(m,k)
         D1      D2      D3      Export
PS       0       0       0       0
OPF      0       0       0       0
EFB      0       0       0       0
PKT      0       0       0       0
PMF      0       0       0       0
SW       0       0       0       0
HW       0       0       0       0
BO       1600    0       0       0
BE       1550    0       0       0
SG       0       860     350     0
PW       0       0       1200    0         ;

Table demand_lower(m,k)
         D1      D2      D3      Export
```

```
PS       0       0       0       0
OPF      0       0       0       0
EFB      0       0       0       0
PKT      0       0       0       0
PMF      0       0       0       0
SW       0       0       0       0
HW       0       0       0       0
BO       1600    0       0       0
BE       1550    0       0       0
SG       0       860     350     0
PW       0       0       1200    0        ;

* Biomass recycle contraint factor (no product is being recycle)
Table TtoTfactor(m,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       1       1       1       1       1
OPF      1       1       1       1       1
EFB      1       1       1       1       1
PKT      1       1       1       1       1
PMF      1       1       1       1       1
SW       1       1       1       1       1
HW       1       1       1       1       1
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0   ;


Equation
E1(i,m), E2(m,j), E3(m,jp), E4(m,jp), E5(m,k), E5b(m,k), E2b(j);

* Resources constraint
E1(i,m).. sum((j), RtoT(i,m,j))=l=resource(i,m);

* Total material received at T
E2(m,j)..
sum((i),RtoT(i,m,j))+(sum((jp),TtoT(jp,m,j))*TtoTfactor(m,j))=e=MatRe
cT(m,j);

E2b(j)..         sum((m),(MatRecT(m,j)))=e=TMatRecT(j);


* ELEMENT
Table element(m,e)
         Cel     Hcel    Lig     Ext     Ash     MC
PS       0.277   0.216   0.440   0.02    0.021   0.11
OPF      0.304   0.404   0.217   0.027   0.013   0.16
EFB      0.373   0.146   0.317   0.013   0.067   0.10
PKT      0.345   0.318   0.257   0.027   0.043   0.130
PMF      0.339   0.261   0.277   0.069   0.035   0.131
SW       0.375   0.275   0.285   0.025   0.035   0.14
HW       0.475   0.275   0.225   0.025   0.035   0.14
BO       0       0       0       0       0       0
BE       0       0       0       0       0       0
SG       0       0       0       0       0       0
PW       0       0       0       0       0       0        ;

Table e_upper(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.327   0.354   0.354   0.354   0.423
Hcel     0.266   0.454   0.454   0.454   0.196
```

```
Lig      0.49    0.267   0.267   0.267   0.367
Ext      0.07    0.077   0.077   0.077   0.063
Ash      0.071   0.063   0.063   0.063   0.117
MC       0.16    0.21    0.21    0.21    0.15   ;

Table e_lower(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.227   0.254   0.254   0.254   0.323
Hcel     0.166   0.354   0.354   0.354   0.096
Lig      0.39    0.167   0.167   0.167   0.267
Ext      0       0       0       0       0
Ash      0       0       0       0       0.017
MC       0.06    0.11    0.11    0.11    0.05        ;


Positive Variable
EleRecT(m,e,j),Z3b(e,j);

Equation
E6(m,e,j), E6b(e,j), E7(e,j), E8(e,j);

* Element received at T
E6(m,e,j).. MatRecT(m,j)*element(m,e)=e=EleRecT(m,e,j) ;

* Sum of element (tonne) at T
E6b(e,j)..  sum((m),EleRecT(m,e,j))=e=Z3b(e,j);

E7(e,j).. sum((m),EleRecT(m,e,j))=l=e_upper(e,j)*TMatRecT(j);
E8(e,j).. sum((m),EleRecT(m,e,j))=g=e_lower(e,j)*TMatRecT(j);

*ELEMENT end


*MASS cont..


*Total material product at T
E3(m,jp).. TMatRecT('1_T1')*yield1_T1(m,jp) +
TMatRecT('2_T2')*yield2_T2(m,jp) + TMatRecT('2_T3')*yield2_T3(m,jp) +
TMatRecT('3_T2')*yield3_T2(m,jp) +
TMatRecT('4_T4')*yield4_T4(m,jp)=e=MatGenT(m,jp);



* Product constraint
E4(m,jp)..
(sum((k),TtoD(jp,m,k))+sum((j),TtoT(jp,m,j)))=l=MatGenT(m,jp);

* Demand constraint
E5(m,k).. sum((jp),TtoD(jp,m,k))=l=demand_upper(m,k);
E5b(m,k).. sum((jp),TtoD(jp,m,k))=g=demand_lower(m,k);


* MASS end


* Transportation
Parameter
transcost transportation cost RM per tonne per km / 0.5 /;

Positive Variables
```

```
Cost_RtoT(i,j), Cost_TtoT(j,jp), Cost_TtoD(jp,k), Ttranscost;

Table distance_RtoT(i,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
R1       600.0   360.6   360.6   854.4   565.7
R2       608.3   583.1   583.1   447.2   360.6
R3       1063.0  583.1   583.1   400.0   640.3
R4       721.1   223.6   223.6   500.0   400.0     ;

Table distance_TtoT(j,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
1_T1     0       500.0   500.0   584.4   447.2
2_T2     500.0   0       0       509.9   223.6
2_T3     500.0   0       0       509.9   223.6
3_T2     854.4   509.9   509.0   0       412.3
4_T4     447.2   223.6   223.6   412.3   0     ;

Table distance_TtoD(jp,k)
         D1      D2      D3      Export
1_T1     640.3   300.0   500.0   905.5
2_T2     200.0   400.0   0       781.0
2_T3     200.0   400.0   0       781.0
3_T2     316.2   583.1   509.9   412.3
4_T4     223.6   223.6   223.6   583.1  ;

Equations
E9(i,j), E10(j,jp), E11(jp,k), E12;

E9(i,j)..
(sum((m),RtoT(i,m,j))*distance_RtoT(i,j)*transcost)=e=Cost_RtoT(i,j);
E10(j,jp)..
(sum((m),TtoT(j,m,jp))*distance_TtoT(j,jp)*transcost)=e=Cost_TtoT(j,j
p);
E11(jp,k)..
(sum((m),TtoD(jp,m,k))*distance_TtoD(jp,k)*transcost)=e=Cost_TtoD(jp,
k);
E12..
(sum((i,j),Cost_RtoT(i,j)))+(sum((j,jp),Cost_TtoT(j,jp)))+(sum((jp,k)
,Cost_TtoD(jp,k)))=e=Ttranscost;

* TRANSPORTATION end


* Profit
Parameter
value(m) selling value /PS 120, OPF 110, EFB 105, PKT 65, PMF 75, SW
50, HW 85, BO 300, BE 450, SG 325, PW 260/;

Positive Variable
Z7(m),Z7b, Z8(m), Z9(m),Z9b, profit;

Variable
totalprofit;

Equation
E13(m),E13b, E15(m),E15b, E16, obj  ;

* Total resources used in R
E13(m).. sum((i,j),RtoT(i,m,j))=e=Z7(m);

* Total amount used in purchasing raw material
```

```
E13b.. sum((m),((Z7(m))*value(m)))=e=Z7b;

* Total product send to D
E15(m).. sum((jp,k),TtoD(jp,m,k))=e=Z9(m);

* Total sell in D
E15b.. sum((m),((Z9(m))*value(m)))=e=Z9b;

E16.. Z9b-Z7b=e=profit;
obj.. Totalprofit=e=profit-Ttranscost ;


Model MarkII /all/;

Solve MarkII using LP maximising Totalprofit;

display RtoT.l, TtoT.l, TtoD.l;
```

Case study 2A

```
*Model formulation for sub-case study 2A

set
i resources /R1, R2, R3, R4/
j technology /1_T1, 2_T2, 2_T3, 3_T2, 4_T4/
k demand /D1, D2, D3, Export/
m material /PS, OPF, EFB, PKT, PMF, SW, HW, BO, BE, SG, PW/
e element /Cel, Hcel, Lig, Ext, Ash, MC/

alias (j,jp) ;

Positive variables
RtoT(i,m,j), TtoT(jp,m,j), TtoD(jp,m,k);

Positive Variables
MatRecT(m,j), TMatRecT(j), MatGenT(m,jp), Zz(j) ;

* MASS

* resources availability
Table resource(i,m)
         PS      OPF     EFB     PKT     PMF     SW      HW      BO
BE      SG      PW
R1       2500    1500    2000    0       0       0       0       0
0       0       0
R2       1750    2300    2100    0       0       0       0       0
0       0       0
R3       0       0       0       0       0       0       0       0
0       0       0
R4       0       0       0       0       0       0       0       0
0       0       0;


* technology conversion
Table yield1_T1(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0.461   0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0;

Table yield2_T2(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       1.94    0       0       0
BE       0       0       0       0       0
```

```
SG       0       0       0       0       0
PW       0       0       0       0       0;

Table yield2_T3(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       10.30   0       0;

Table yield3_T2(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       10.3    0
PW       0       0       0       0       0;

Table yield4_T4(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0.2416
SG       0       0       0       0       0
PW       0       0       0       0       0;

* demand constraint
Table demand_upper(m,k)
         D1      D2      D3      Export
PS       0       0       0       0
OPF      0       0       0       0
EFB      0       0       0       0
PKT      0       0       0       0
PMF      0       0       0       0
SW       0       0       0       0
HW       0       0       0       0
BO       1600    0       0       999999999990
BE       1550    0       0       99999999999990
SG       0       860     350     999999999990
PW       0       0       1200    0         ;

Table demand_lower(m,k)
```

```
         D1      D2      D3      Export
PS       0       0       0       0
OPF      0       0       0       0
EFB      0       0       0       0
PKT      0       0       0       0
PMF      0       0       0       0
SW       0       0       0       0
HW       0       0       0       0
BO       1600    0       0       0
BE       1550    0       0       0
SG       0       860     350     0
PW       0       0       1200    0        ;

* Biomass recycle contraint factor (no product is being recycle)
Table TtoTfactor(m,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       1       1       1       1       1
OPF      1       1       1       1       1
EFB      1       1       1       1       1
PKT      1       1       1       1       1
PMF      1       1       1       1       1
SW       1       1       1       1       1
HW       1       1       1       1       1
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0   ;


Equation
E1(i,m), E2(m,j), E3(m,jp), E4(m,jp), E5(m,k), E5b(m,k), E2b(j);

* Resources constraint
E1(i,m).. sum((j), RtoT(i,m,j))=l=resource(i,m);

* Total material received at T
E2(m,j)..
sum((i),RtoT(i,m,j))+(sum((jp),TtoT(jp,m,j))*TtoTfactor(m,j))=e=MatRe
cT(m,j);

E2b(j)..         sum((m),(MatRecT(m,j)))=e=TMatRecT(j);


* ELEMENT
Table element(m,e)
         Cel     Hcel    Lig     Ext     Ash     MC
PS       0.277   0.216   0.440   0.02    0.021   0.11
OPF      0.304   0.404   0.217   0.027   0.013   0.16
EFB      0.373   0.146   0.317   0.013   0.067   0.10
PKT      0.345   0.318   0.257   0.027   0.043   0.130
PMF      0.339   0.261   0.277   0.069   0.035   0.131
SW       0.375   0.275   0.285   0.025   0.035   0.14
HW       0.475   0.275   0.225   0.025   0.035   0.14
BO       0       0       0       0       0       0
BE       0       0       0       0       0       0
SG       0       0       0       0       0       0
PW       0       0       0       0       0       0        ;

Table e_upper(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.327   0.354   0.354   0.354   0.423
```

```
Hcel      0.266   0.454   0.454   0.454   0.196
Lig       0.49    0.267   0.267   0.267   0.367
Ext       0.07    0.077   0.077   0.077   0.063
Ash       0.071   0.063   0.063   0.063   0.117
MC        0.16    0.21    0.21    0.21    0.15   ;

Table e_lower(e,j)
          1_T1    2_T2    2_T3    3_T2    4_T4
Cel       0.227   0.254   0.254   0.254   0.323
Hcel      0.166   0.354   0.354   0.354   0.096
Lig       0.39    0.167   0.167   0.167   0.267
Ext       0       0       0       0       0
Ash       0       0       0       0       0.017
MC        0.06    0.11    0.11    0.11    0.05        ;


Positive Variable
EleRecT(m,e,j),Z3b(e,j);

Equation
E6(m,e,j), E6b(e,j), E7(e,j), E8(e,j);

* Element received at T
E6(m,e,j).. MatRecT(m,j)*element(m,e)=e=EleRecT(m,e,j) ;

* Sum of element (tonne) at T
E6b(e,j)..  sum((m),EleRecT(m,e,j))=e=Z3b(e,j);

E7(e,j).. sum((m),EleRecT(m,e,j))=l=e_upper(e,j)*TMatRecT(j);
E8(e,j).. sum((m),EleRecT(m,e,j))=g=e_lower(e,j)*TMatRecT(j);

*ELEMENT end


*MASS cont..


*Total material product at T
E3(m,jp).. TMatRecT('1_T1')*yield1_T1(m,jp) +
TMatRecT('2_T2')*yield2_T2(m,jp) + TMatRecT('2_T3')*yield2_T3(m,jp) +
TMatRecT('3_T2')*yield3_T2(m,jp) +
TMatRecT('4_T4')*yield4_T4(m,jp)=e=MatGenT(m,jp);


* Product constraint
E4(m,jp)..
(sum((k),TtoD(jp,m,k))+sum((j),TtoT(jp,m,j)))=l=MatGenT(m,jp);

* Demand constraint
E5(m,k).. sum((jp),TtoD(jp,m,k))=l=demand_upper(m,k);
E5b(m,k).. sum((jp),TtoD(jp,m,k))=g=demand_lower(m,k);


* MASS end


* Transportation
Parameter
transcost transportation cost RM per tonne per km / 0.5 /;

Positive Variables
```

```
Cost_RtoT(i,j), Cost_TtoT(j,jp), Cost_TtoD(jp,k), Ttranscost;

Table distance_RtoT(i,j)
         1_T1     2_T2     2_T3     3_T2     4_T4
R1       600.0    360.6    360.6    854.4    565.7
R2       608.3    583.1    583.1    447.2    360.6
R3       1063.0   583.1    583.1    400.0    640.3
R4       721.1    223.6    223.6    500.0    400.0     ;

Table distance_TtoT(j,jp)
         1_T1     2_T2     2_T3     3_T2     4_T4
1_T1     0        500.0    500.0    584.4    447.2
2_T2     500.0    0        0        509.9    223.6
2_T3     500.0    0        0        509.9    223.6
3_T2     854.4    509.9    509.0    0        412.3
4_T4     447.2    223.6    223.6    412.3    0     ;

Table distance_TtoD(jp,k)
         D1       D2       D3       Export
1_T1     640.3    300.0    500.0    905.5
2_T2     200.0    400.0    0        781.0
2_T3     200.0    400.0    0        781.0
3_T2     316.2    583.1    509.9    412.3
4_T4     223.6    223.6    223.6    583.1  ;

Equations
E9(i,j), E10(j,jp), E11(jp,k), E12;

E9(i,j)..
(sum((m),RtoT(i,m,j))*distance_RtoT(i,j)*transcost)=e=Cost_RtoT(i,j);
E10(j,jp)..
(sum((m),TtoT(j,m,jp))*distance_TtoT(j,jp)*transcost)=e=Cost_TtoT(j,j
p);
E11(jp,k)..
(sum((m),TtoD(jp,m,k))*distance_TtoD(jp,k)*transcost)=e=Cost_TtoD(jp,
k);
E12..
(sum((i,j),Cost_RtoT(i,j)))+(sum((j,jp),Cost_TtoT(j,jp)))+(sum((jp,k)
,Cost_TtoD(jp,k)))=e=Ttranscost;

* TRANSPORTATION end


* Profit
Parameter
value(m) selling value /PS 120, OPF 110, EFB 105, PKT 65, PMF 75, SW
50, HW 85, BO 300, BE 450, SG 325, PW 260/;

Positive Variable
Z7(m),Z7b, Z8(m), Z9(m),Z9b, profit;

Variable
totalprofit;

Equation
E13(m),E13b, E15(m),E15b, E16, obj  ;

* Total resources used in R
E13(m).. sum((i,j),RtoT(i,m,j))=e=Z7(m);

* Total amount used in purchasing raw material
```

```
E13b.. sum((m),((Z7(m))*value(m)))=e=Z7b;

* Total product send to D
E15(m).. sum((jp,k),TtoD(jp,m,k))=e=Z9(m);

* Total sell in D
E15b.. sum((m),((Z9(m))*value(m)))=e=Z9b;

E16.. Z9b-Z7b=e=profit;
obj.. Totalprofit=e=profit-Ttranscost ;


Model MarkII /all/;

Solve MarkII using LP maximising Totalprofit;

display RtoT.l, TtoT.l, TtoD.l;
```

Case study 2B

```
*Model formulation for sub-case study 2B

set
i resources /R1, R2, R3, R4/
j technology /1_T1, 2_T2, 2_T3, 3_T2, 4_T4/
k demand /D1, D2, D3, Export/
m material /PS, OPF, EFB, PKT, PMF, SW, HW, BO, BE, SG, PW/
e element /Cel, Hcel, Lig, Ext, Ash, MC/

alias (j,jp) ;

Positive variables
RtoT(i,m,j), TtoT(jp,m,j), TtoD(jp,m,k);

Positive Variables
MatRecT(m,j), TMatRecT(j), MatGenT(m,jp), Zz(j) ;

* MASS

* resources availability
Table resource(i,m)
         PS      OPF     EFB     PKT     PMF     SW      HW      BO
BE      SG      PW
R1       2500    1500    2000    800     0       0       0       0
0       0       0
R2       1750    2300    2100    0       750     0       0       0
0       0       0
R3       0        0      0       0       0       1500    0       0
0       0       0
R4       0        0      0       0       0       0       1750    0
0       0       0;

* technology conversion
Table yield1_T1(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0.461   0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0;

Table yield2_T2(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       1.94    0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
```

```
PW        0        0        0        0        0;

Table yield2_T3(m,jp)
          1_T1     2_T2     2_T3     3_T2     4_T4
PS        0        0        0        0        0
OPF       0        0        0        0        0
EFB       0        0        0        0        0
PKT       0        0        0        0        0
PMF       0        0        0        0        0
SW        0        0        0        0        0
HW        0        0        0        0        0
BO        0        0        0        0        0
BE        0        0        0        0        0
SG        0        0        0        0        0
PW        0        0        10.30    0        0;

Table yield3_T2(m,jp)
          1_T1     2_T2     2_T3     3_T2     4_T4
PS        0        0        0        0        0
OPF       0        0        0        0        0
EFB       0        0        0        0        0
PKT       0        0        0        0        0
PMF       0        0        0        0        0
SW        0        0        0        0        0
HW        0        0        0        0        0
BO        0        0        0        0        0
BE        0        0        0        0        0
SG        0        0        0        10.3     0
PW        0        0        0        0        0;

Table yield4_T4(m,jp)
          1_T1     2_T2     2_T3     3_T2     4_T4
PS        0        0        0        0        0
OPF       0        0        0        0        0
EFB       0        0        0        0        0
PKT       0        0        0        0        0
PMF       0        0        0        0        0
SW        0        0        0        0        0
HW        0        0        0        0        0
BO        0        0        0        0        0
BE        0        0        0        0        0.2416
SG        0        0        0        0        0
PW        0        0        0        0        0;

* demand constraint
Table demand_upper(m,k)
          D1       D2       D3       Export
PS        0        0        0        0
OPF       0        0        0        0
EFB       0        0        0        0
PKT       0        0        0        0
PMF       0        0        0        0
SW        0        0        0        0
HW        0        0        0        0
BO        1600     0        0        99999999990
BE        1550     0        0        99999999990
SG        0        860      350      999999999990
PW        0        0        1200     0          ;

Table demand_lower(m,k)
          D1       D2       D3       Export
```

```
PS       0       0       0       0
OPF      0       0       0       0
EFB      0       0       0       0
PKT      0       0       0       0
PMF      0       0       0       0
SW       0       0       0       0
HW       0       0       0       0
BO       1600    0       0       0
BE       1550    0       0       0
SG       0       860     350     0
PW       0       0       1200    0        ;

* Biomass recycle contraint factor (no product is being recycle)
Table TtoTfactor(m,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       1       1       1       1       1
OPF      1       1       1       1       1
EFB      1       1       1       1       1
PKT      1       1       1       1       1
PMF      1       1       1       1       1
SW       1       1       1       1       1
HW       1       1       1       1       1
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0   ;


Equation
E1(i,m), E2(m,j), E3(m,jp), E4(m,jp), E5(m,k), E5b(m,k), E2b(j);

* Resources constraint
E1(i,m).. sum((j), RtoT(i,m,j))=l=resource(i,m);

* Total material received at T
E2(m,j)..
sum((i),RtoT(i,m,j))+(sum((jp),TtoT(jp,m,j))*TtoTfactor(m,j))=e=MatRe
cT(m,j);

E2b(j)..         sum((m),(MatRecT(m,j)))=e=TMatRecT(j);


* ELEMENT
Table element(m,e)
         Cel     Hcel    Lig     Ext     Ash     MC
PS       0.277   0.216   0.440   0.02    0.021   0.11
OPF      0.304   0.404   0.217   0.027   0.013   0.16
EFB      0.373   0.146   0.317   0.013   0.067   0.10
PKT      0.345   0.318   0.257   0.027   0.043   0.130
PMF      0.339   0.261   0.277   0.069   0.035   0.131
SW       0.375   0.275   0.285   0.025   0.035   0.14
HW       0.475   0.275   0.225   0.025   0.035   0.14
BO       0       0       0       0       0       0
BE       0       0       0       0       0       0
SG       0       0       0       0       0       0
PW       0       0       0       0       0       0        ;

Table e_upper(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.327   0.354   0.354   0.354   0.423
Hcel     0.266   0.454   0.454   0.454   0.196
```

```
Lig      0.49    0.267   0.267   0.267   0.367
Ext      0.07    0.077   0.077   0.077   0.063
Ash      0.071   0.063   0.063   0.063   0.117
MC       0.16    0.21    0.21    0.21    0.15   ;

Table e_lower(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.227   0.254   0.254   0.254   0.323
Hcel     0.166   0.354   0.354   0.354   0.096
Lig      0.39    0.167   0.167   0.167   0.267
Ext      0       0       0       0       0
Ash      0       0       0       0       0.017
MC       0.06    0.11    0.11    0.11    0.05        ;


Positive Variable
EleRecT(m,e,j),Z3b(e,j);

Equation
E6(m,e,j), E6b(e,j), E7(e,j), E8(e,j);

* Element received at T
E6(m,e,j).. MatRecT(m,j)*element(m,e)=e=EleRecT(m,e,j) ;

* Sum of element (tonne) at T
E6b(e,j)..  sum((m),EleRecT(m,e,j))=e=Z3b(e,j);

E7(e,j).. sum((m),EleRecT(m,e,j))=l=e_upper(e,j)*TMatRecT(j);
E8(e,j).. sum((m),EleRecT(m,e,j))=g=e_lower(e,j)*TMatRecT(j);

*ELEMENT end


*MASS cont..


*Total material product at T
E3(m,jp).. TMatRecT('1_T1')*yield1_T1(m,jp) +
TMatRecT('2_T2')*yield2_T2(m,jp) + TMatRecT('2_T3')*yield2_T3(m,jp) +
TMatRecT('3_T2')*yield3_T2(m,jp) +
TMatRecT('4_T4')*yield4_T4(m,jp)=e=MatGenT(m,jp);


* Product constraint
E4(m,jp)..
(sum((k),TtoD(jp,m,k))+sum((j),TtoT(jp,m,j)))=l=MatGenT(m,jp);

* Demand constraint
E5(m,k).. sum((jp),TtoD(jp,m,k))=l=demand_upper(m,k);
E5b(m,k).. sum((jp),TtoD(jp,m,k))=g=demand_lower(m,k);


* MASS end


* Transportation
Parameter
transcost transportation cost RM per tonne per km / 0.5 /;

Positive Variables
Cost_RtoT(i,j), Cost_TtoT(j,jp), Cost_TtoD(jp,k), Ttranscost;
```

```
Table distance_RtoT(i,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
R1       600.0   360.6   360.6   854.4   565.7
R2       608.3   583.1   583.1   447.2   360.6
R3       1063.0  583.1   583.1   400.0   640.3
R4       721.1   223.6   223.6   500.0   400.0     ;

Table distance_TtoT(j,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
1_T1     0       500.0   500.0   584.4   447.2
2_T2     500.0   0       0       509.9   223.6
2_T3     500.0   0       0       509.9   223.6
3_T2     854.4   509.9   509.0   0       412.3
4_T4     447.2   223.6   223.6   412.3   0     ;

Table distance_TtoD(jp,k)
         D1      D2      D3      Export
1_T1     640.3   300.0   500.0   905.5
2_T2     200.0   400.0   0       781.0
2_T3     200.0   400.0   0       781.0
3_T2     316.2   583.1   509.9   412.3
4_T4     223.6   223.6   223.6   583.1  ;

Equations
E9(i,j), E10(j,jp), E11(jp,k), E12;

E9(i,j)..
(sum((m),RtoT(i,m,j))*distance_RtoT(i,j)*transcost)=e=Cost_RtoT(i,j);
E10(j,jp)..
(sum((m),TtoT(j,m,jp))*distance_TtoT(j,jp)*transcost)=e=Cost_TtoT(j,j
p);
E11(jp,k)..
(sum((m),TtoD(jp,m,k))*distance_TtoD(jp,k)*transcost)=e=Cost_TtoD(jp,
k);
E12..
(sum((i,j),Cost_RtoT(i,j)))+(sum((j,jp),Cost_TtoT(j,jp)))+(sum((jp,k)
,Cost_TtoD(jp,k)))=e=Ttranscost;

* TRANSPORTATION end


* Profit
Parameter
value(m) selling value /PS 120, OPF 110, EFB 105, PKT 65, PMF 75, SW
50, HW 85, BO 300, BE 450, SG 325, PW 260/;

Positive Variable
Z7(m),Z7b, Z8(m), Z9(m),Z9b, profit;

Variable
totalprofit;

Equation
E13(m),E13b, E15(m),E15b, E16, obj  ;

* Total resources used in R
E13(m).. sum((i,j),RtoT(i,m,j))=e=Z7(m);

* Total amount used in purchasing raw material
E13b.. sum((m),((Z7(m))*value(m)))=e=Z7b;
```

```
* Total product send to D
E15(m).. sum((jp,k),TtoD(jp,m,k))=e=Z9(m);

* Total sell in D
E15b.. sum((m),((Z9(m))*value(m)))=e=Z9b;

E16.. Z9b-Z7b=e=profit;
obj.. Totalprofit=e=profit-Ttranscost ;


Model MarkII /all/;

Solve MarkII using LP maximising Totalprofit;

display RtoT.l, TtoT.l, TtoD.l;
```

APPENDIX II

Case study A

```
* Case study A: Conventional approach

set
i resources /R1, R2, R3, R4, R5, R6/
j technology /T1, T2, T3, T3b, T4/
k demand /D1, D2, D3, D4, Export/
m material /Cc, Pw, Hn, Tr, Cr, Tw, Po, H2, Bio-E, Gp/
e element /Ash, FC, VM, MC, HV, Cell, H-cell/

alias (j,jp) ;

Positive variables
RtoT(i,m,j), TtoT(jp,m,j), TtoD(jp,m,k);

Positive Variables
Z1(m,j), Z1b(j), Z2(m,jp), Zz(j) ;

* MASS

* resources availability
Table resource(i,m)
         Cc      Pw      Hn      Tr      Cr      Tw      Po      H2
Bio-E   Gp
R1       3000000 0       0       0       0       0       0       0
0       0
R2       0       2400000 0       0       0       0       0       0
0       0
R3       0       0       0       0       0       0       0       0
0       0
R4       0       0       0       0       0       0       0       0
0       0
R5       0       0       0       0       0       0       0       0
0       0
R6       0       0       0       0       0       0       0       0
0       0;


* technology conversion
Table yieldT1(m,jp)
         T1      T2      T3      T3b     T4
Cc       0       0       0       0       0
Pw       0       0       0       0       0
Hn       0       0       0       0       0
Tr       0       0       0       0       0
Cr       0       0       0       0       0
Tw       0       0       0       0       0
Po       0       0       0       0       0
H2       0.03046 0       0       0       0
Bio-E    0       0       0       0       0
Gp       0       0       0       0       0;

Table yieldT2(m,jp)
         T1      T2      T3      T3b     T4
```

```
Cc        0        0        0        0        0
Pw        0        0        0        0        0
Hn        0        0        0        0        0
Tr        0        0        0        0        0
Cr        0        0        0        0        0
Tw        0        0        0        0        0
Po        0        0.68     0        0        0
H2        0        0        0        0        0
Bio-E     0        0        0        0        0
Gp        0        0.056    0        0        0;

Table yieldT3(m,jp)
          T1       T2       T3       T3b      T4
Cc        0        0        0        0        0
Pw        0        0        0        0        0
Hn        0        0        0        0        0
Tr        0        0        0        0        0
Cr        0        0        0        0        0
Tw        0        0        0        0        0
Po        0        0        0        0        0
H2        0        0        0        0        0
Bio-E     0        0        0.29     0        0
Gp        0        0        0        0        0;

Table yieldT3b(m,jp)
          T1       T2       T3       T3b      T4
Cc        0        0        0        0        0
Pw        0        0        0        0        0
Hn        0        0        0        0        0
Tr        0        0        0        0        0
Cr        0        0        0        0        0
Tw        0        0        0        0        0
Po        0        0        0        0        0
H2        0        0        0        0        0
Bio-E     0        0        0        0.23     0
Gp        0        0        0        0        0;

Table yieldT4(m,jp)
          T1       T2       T3       T3b      T4
Cc        0        0        0        0        0
Pw        0        0        0        0        0
Hn        0        0        0        0        0
Tr        0        0        0        0        0
Cr        0        0        0        0        0
Tw        0        0        0        0        0
Po        0        0        0        0        0.3
H2        0        0        0        0        0
Bio-E     0        0        0        0        0
Gp        0        0        0        0        0;

Table production_cost(m,jp)
          T1       T2       T3       T3b      T4
Cc        0        0        0        0        0
Pw        0        0        0        0        0
Hn        0        0        0        0        0
Tr        0        0        0        0        0
Cr        0        0        0        0        0
Tw        0        0        0        0        0
Po        0        0.019    0        0        0.0152
H2        4.92     0        0        0        0
Bio-E     0        0        0.57     0.57     0
```

```
Gp       0       0       0       0       0;

* demand constraint
Table demand_upper(m,k)
         D1      D2      D3      D4      Export
Cc       0       0       0       0       0
Pw       0       0       0       0       0
Hn       0       0       0       0       0
Tr       0       0       0       0       0
Cr       0       0       0       0       0
Tw       0       0       0       0       0
Po       0       0       50000   70000   9999999999999999
H2       5000    20000   0       0       9999999999999999
Bio-E    15000   13000   0       0       9999999999999999
Gp       0       0       0       0       0        ;

Table demand_lower(m,k)
         D1      D2      D3      D4      Export
Cc       0       0       0       0       0
Pw       0       0       0       0       0
Hn       0       0       0       0       0
Tr       0       0       0       0       0
Cr       0       0       0       0       0
Tw       0       0       0       0       0
Po       0       0       50000   70000   0
H2       5000    20000   0       0       0
Bio-E    0       0       0       0       0
Gp       0       0       0       0       0        ;

* Biomass recycle contraint factor (no product is being recycle)
Table TtoTfactor(m,j)
         T1      T2      T3      T3b     T4
Cc       1       1       1       1       1
Pw       1       1       1       1       1
Hn       1       1       1       1       1
Tr       1       1       1       1       1
Cr       1       1       1       1       1
Tw       1       1       1       1       1
Po       0       0       0       0       0
H2       0       0       0       0       0
Bio-E    0       0       0       0       0
Gp       1       1       1       1       1   ;


Equation
E1(i,m), E2(m,j), E3(m,jp), E4(m,jp), E5(m,k),E5b(m,k), E2b(j),
E4b(jp,m);

* Resources constraint
E1(i,m).. sum((j), RtoT(i,m,j))=l=resource(i,m);

* Total material received at T
E2(m,j)..
sum((i),RtoT(i,m,j))+(sum((jp),TtoT(jp,m,j))*TtoTfactor(m,j))=e=Z1(m,
j);

E2b(j)..         sum((m),(Z1(m,j)))=e=Z1b(j);


* ELEMENT
Table element(m,e)
```

```
          Ash     FC      VM      MC      HV      Cell    H-cell
Cc        0.029   0.174   0.727   0.07    0.192   0.30    0.15
Pw        0.016   0.19    0.713   0.08    0.212   0.40    0.200
Hn        0.017   0.18    0.735   0.068   0.194   0.382   0.121
Tr        0.037   0.165   0.723   0.075   0.19    0.24    0.17
Cr        0.15    0.067   0.663   0.12    0.158   0.311   0.054
Tw        0.049   0.0     0.803   0.148   0.196   0.38    0.25
Po        0       0       0       0       0       0       0
H2        0       0       0       0       0       0       0
Bio-E     0       0       0       0       0       0       0
Gp        0.081   0.844   0.065   0.01    0.299   0       0  ;

Table e_upper(e,j)
          T1      T2      T3      T3b     T4
Ash       0.029   0.016   0       0       0
FC        0.174   0.19    0       0       0
VM        0.727   0.713   0       0       0
MC        0.07    0.08    0       0       0
HV        0.192   0.212   0       0       0
Cell      0.30    0.40    0       0       0
H-cell    0.15    0.20    0       0       0     ;

Table e_lower(e,j)
          T1      T2      T3      T3b     T4
Ash       0.029   0.016   0       0       0
FC        0.174   0.19    0       0       0
VM        0.727   0.713   0       0       0
MC        0.07    0.08    0       0       0
HV        0.192   0.212   0       0       0
Cell      0.30    0.40    0       0       0
H-cell    0.15    0.20    0       0       0     ;


Positive Variable
Z3(m,e,j),Z3b(e,j),Z3c(e,j),Z3d(e,j);

Equation
E6(m,e,j), E6b(e,j), E7(e,j), E8(e,j),E6c(e,j),E6d(e,j);

* Element received at T
E6(m,e,j).. Z1(m,j)*element(m,e)=e=Z3(m,e,j) ;

* Sum of element (tonne) at T
E6b(e,j)..  sum((m),Z3(m,e,j))=e=Z3b(e,j);

E6c(e,j)..  e_upper(e,j)*Z1b(j)=e=Z3c(e,j);
E6d(e,j)..  e_lower(e,j)*Z1b(j)=e=Z3d(e,j);


E7(e,j).. sum((m),Z3(m,e,j))=l=e_upper(e,j)*Z1b(j);
E8(e,j).. sum((m),Z3(m,e,j))=g=e_lower(e,j)*Z1b(j);

*ELEMENT end


*MASS cont..


*Total material product at T
```

```
E3(m,jp).. Z1b('T1')*yieldT1(m,jp) + Z3b('Hv','T2')*yieldT2(m,jp) +
Z3b('Cell','T3')*yieldT3(m,jp) + Z3b('H-cell','T3b')*yieldT3b(m,jp) +
Z3b('Hv','T4')*yieldT4(m,jp)=e=Z2(m,jp);



* Product constraint
E4(m,jp).. (sum((k),TtoD(jp,m,k))+sum((j),TtoT(jp,m,j)))=l=Z2(m,jp);

*Recycle constraint
E4b(jp,m)..    sum((j),TtoT(jp,m,j))=l=Z2(m,jp)-
sum((k),TtoD(jp,m,k));

* Demand constraint
E5(m,k).. sum((jp),TtoD(jp,m,k))=l=demand_upper(m,k);
E5b(m,k).. sum((jp),TtoD(jp,m,k))=g=demand_lower(m,k);


* MASS end


* Transportation
Parameter
transcost transportation cost $ per tonne per km / 0.0001 /;

Positive Variables
Z4(i,j), Z5(j,jp), Z6(jp,k), Ttranscost;

Table distance_RtoT(i,j)
         T1      T2      T3      T3b     T4
R1       40.00   36.06   89.44   89.44   44.72
R2       31.62   53.85   76.16   76.16   58.31
R3       94.34   58.31   50.00   50.00   50.00
R4       64.03   31.62   64.03   64.03   30.00
R5       50.00   28.28   30.00   30.00   22.36
R6       76.16   64.03   31.62   31.62   58.31     ;

Table distance_TtoT(j,jp)
         T1      T2      T3      T3b     T4
T1       0.00    36.05   80.00   80.00   44.72
T2       36.06   0.00    53.85   53.85   10.00
T3       80.00   53.85   0.00    0.00    44.72
T3b      80.00   53.85   0.00    0.00    44.72
T4       44.72   10.00   44.72   44.72   0.00     ;

Table distance_TtoD(jp,k)
         D1      D2      D3      D4      Export
T1       53.85   36.06   36.06   44.72   94.87
T2       20.00   40.00   0.00    10.00   78.10
T3       36.06   53.85   53.85   44.72   31.62
T3b      36.06   53.85   53.85   44.72   31.62
T4       0.00    41.23   10.00   0.00    70.71 ;

Equations
E9(i,j), E10(j,jp), E11(jp,k), E12;

E9(i,j)..
(sum((m),RtoT(i,m,j))*distance_RtoT(i,j)*transcost)=e=Z4(i,j);
E10(j,jp)..
(sum((m),TtoT(j,m,jp))*distance_TtoT(j,jp)*transcost)=e=Z5(j,jp);
```

```
E11(jp,k)..
(sum((m),TtoD(jp,m,k))*distance_TtoD(jp,k)*transcost)=e=Z6(jp,k);
E12..
(sum((i,j),Z4(i,j)))+(sum((j,jp),Z5(j,jp)))+(sum((jp,k),Z6(jp,k)))=e=
Ttranscost;

* TRANSPORTATION end


* Profit
Parameter
value(m) selling value /Cc 0.1, Pw 0.190, Hn 0.040, Tr 0.030, Cr
0.025, Tw 0.0475, Po 0.396, H2 10, Bio-E 1.57, Gp 0/;

Positive Variable
Z7(m),Total_biomass_cost, Z8(m,jp), Total_Production_Cost,
Z9(m),Total_sell, profit;

Variable
totalprofit;

Equation
E13(m),E13b, E14(m,jp), E14b, E15(m),E15b, E16, obj  ;

* Total resources used in R
E13(m).. sum((i,j),RtoT(i,m,j))=e=Z7(m);

* Total amount used in purchasing raw material
E13b.. sum((m),((Z7(m))*value(m)))=e=Total_biomass_cost;

* Total production cost
E14(m,jp).. Z2(m,jp)*production_cost(m,jp)=e=z8(m,jp);
E14b.. sum((m,jp),z8(m,jp))=e=Total_Production_Cost;

* Total product send to D
E15(m).. sum((jp,k),TtoD(jp,m,k))=e=Z9(m);

* Total sell in D
E15b.. sum((m),((Z9(m))*value(m)))=e=Total_sell;

E16.. Total_sell-Total_Production_Cost-Total_biomass_cost=e=profit;
obj.. Totalprofit=e=profit-Ttranscost ;


Model MarkII /all/;

Solve MarkII using LP maximising Totalprofit;

display RtoT.l, TtoT.l, TtoD.l, totalprofit.l;
```

Case study B

```
* Case study B: DRVT approach

set
i resources /R1, R2, R3, R4, R5, R6/
j technology /T1, T2, T3, T3b, T4/
k demand /D1, D2, D3, D4, Export/
m material /Cc, Pw, Hn, Tr, Cr, Tw, Po, H2, Bio-E, Gp/
e element /Ash, FC, VM, MC, HV, Cell, H-cell/

alias (j,jp) ;

Positive variables
RtoT(i,m,j), TtoT(jp,m,j), TtoD(jp,m,k);

Positive Variables
Z1(m,j), Z1b(j), Z2(m,jp), Zz(j) ;

* MASS

* resources availability
Table resource(i,m)
         Cc      Pw      Hn      Tr      Cr      Tw      Po      H2
Bio-E   Gp
R1       3000000 0       0       0       0       0       0       0
0       0
R2       0       2400000 0       0       0       500000  0       0
0       0
R3       0       0       300000  0       0       0       0       0
0       0
R4       0       0       0       950000  0       0       0       0
0       0
R5       0       0       0       0       500000  0       0       0
0       0
R6       0       0       0       0       0       1500000 0       0
0       0;


* technology conversion
Table yieldT1(m,jp)
         T1      T2      T3      T3b     T4
Cc       0       0       0       0       0
Pw       0       0       0       0       0
Hn       0       0       0       0       0
Tr       0       0       0       0       0
Cr       0       0       0       0       0
Tw       0       0       0       0       0
Po       0       0       0       0       0
H2       0.03046 0       0       0       0
Bio-E    0       0       0       0       0
Gp       0       0       0       0       0;

Table yieldT2(m,jp)
         T1      T2      T3      T3b     T4
Cc       0       0       0       0       0
Pw       0       0       0       0       0
Hn       0       0       0       0       0
Tr       0       0       0       0       0
Cr       0       0       0       0       0
Tw       0       0       0       0       0
```

```
Po        0       0.68    0       0       0
H2        0       0       0       0       0
Bio-E     0       0       0       0       0
Gp        0       0.056   0       0       0;

Table yieldT3(m,jp)
          T1      T2      T3      T3b     T4
Cc        0       0       0       0       0
Pw        0       0       0       0       0
Hn        0       0       0       0       0
Tr        0       0       0       0       0
Cr        0       0       0       0       0
Tw        0       0       0       0       0
Po        0       0       0       0       0
H2        0       0       0       0       0
Bio-E     0       0       0.29    0       0
Gp        0       0       0       0       0;

Table yieldT3b(m,jp)
          T1      T2      T3      T3b     T4
Cc        0       0       0       0       0
Pw        0       0       0       0       0
Hn        0       0       0       0       0
Tr        0       0       0       0       0
Cr        0       0       0       0       0
Tw        0       0       0       0       0
Po        0       0       0       0       0
H2        0       0       0       0       0
Bio-E     0       0       0       0.23    0
Gp        0       0       0       0       0;

Table yieldT4(m,jp)
          T1      T2      T3      T3b     T4
Cc        0       0       0       0       0
Pw        0       0       0       0       0
Hn        0       0       0       0       0
Tr        0       0       0       0       0
Cr        0       0       0       0       0
Tw        0       0       0       0       0
Po        0       0       0       0       0.3
H2        0       0       0       0       0
Bio-E     0       0       0       0       0
Gp        0       0       0       0       0;

Table production_cost(m,jp)
          T1      T2      T3      T3b     T4
Cc        0       0       0       0       0
Pw        0       0       0       0       0
Hn        0       0       0       0       0
Tr        0       0       0       0       0
Cr        0       0       0       0       0
Tw        0       0       0       0       0
Po        0       0.019   0       0       0.0152
H2        4.92    0       0       0       0
Bio-E     0       0       0.57    0.57    0
Gp        0       0       0       0       0;

* demand constraint
Table demand_upper(m,k)
          D1      D2      D3      D4      Export
Cc        0       0       0       0       0
```

```
Pw       0       0       0       0       0
Hn       0       0       0       0       0
Tr       0       0       0       0       0
Cr       0       0       0       0       0
Tw       0       0       0       0       0
Po       0       0       50000   70000   9999999999999999
H2       5000    20000   0       0       9999999999999999
Bio-E    15000   13000   0       0       9999999999999999
Gp       0       0       0       0       0        ;

Table demand_lower(m,k)
         D1      D2      D3      D4      Export
Cc       0       0       0       0       0
Pw       0       0       0       0       0
Hn       0       0       0       0       0
Tr       0       0       0       0       0
Cr       0       0       0       0       0
Tw       0       0       0       0       0
Po       0       0       50000   70000   0
H2       5000    20000   0       0       0
Bio-E    15000   13000   0       0       0
Gp       0       0       0       0       0        ;

* Biomass recycle contraint factor (no product is being recycle)
Table TtoTfactor(m,j)
         T1      T2      T3      T3b     T4
Cc       1       1       1       1       1
Pw       1       1       1       1       1
Hn       1       1       1       1       1
Tr       1       1       1       1       1
Cr       1       1       1       1       1
Tw       1       1       1       1       1
Po       0       0       0       0       0
H2       0       0       0       0       0
Bio-E    0       0       0       0       0
Gp       0       0       0       0       0   ;


Equation
E1(i,m), E2(m,j), E3(m,jp), E4(m,jp), E5(m,k),E5b(m,k), E2b(j),
E4b(jp,m);

* Resources constraint
E1(i,m).. sum((j), RtoT(i,m,j))=l=resource(i,m);

* Total material received at T
E2(m,j)..
sum((i),RtoT(i,m,j))+(sum((jp),TtoT(jp,m,j))*TtoTfactor(m,j))=e=Z1(m,
j);

E2b(j)..         sum((m),(Z1(m,j)))=e=Z1b(j);


* ELEMENT
Table element(m,e)
         Ash     FC      VM      MC      HV      Cell    H-cell
Cc       0.029   0.174   0.727   0.07    0.192   0.30    0.15
Pw       0.016   0.19    0.713   0.08    0.212   0.40    0.200
Hn       0.017   0.18    0.735   0.068   0.194   0.382   0.121
Tr       0.037   0.165   0.723   0.075   0.19    0.24    0.17
Cr       0.15    0.067   0.663   0.12    0.158   0.311   0.054
```

```
Tw       0.049   0.0     0.803   0.148   0.196   0.38    0.25
Po       0       0       0       0       0       0       0
H2       0       0       0       0       0       0       0
Bio-E    0       0       0       0       0       0       0
Gp       0.081   0.844   0.065   0.01    0.299   0       0  ;

Table e_upper(e,j)
         T1      T2      T3      T3b     T4
Ash      0.03045 0.0168  1       1       1
FC       0.1827  0.1995  1       1       1
VM       0.76335 0.7518  1       1       1
MC       0.0735  0.084   1       1       0.5
HV       0.2016  0.2226  1       1       1
Cell     0.315   0.42    1       1       1
H-cell   0.1575  0.21    1       1       1;

Table e_lower(e,j)
         T1      T2      T3      T3b     T4
Ash      0.02755 0.0152  0       0       0
FC       0.1653  0.1805  0       0       0
VM       0.69065 0.6802  0       0       0
MC       0.0665  0.076   0       0       0
HV       0.1824  0.2014  0       0       0
Cell     0.285   0.38    0       0       0
H-cell   0.1425  0.19    0       0       0     ;


Positive Variable
Z3(m,e,j),Z3b(e,j),Z3c(e,j),Z3d(e,j);

Equation
E6(m,e,j), E6b(e,j), E7(e,j), E8(e,j),E6c(e,j),E6d(e,j);

* Element received at T
E6(m,e,j).. Z1(m,j)*element(m,e)=e=Z3(m,e,j) ;

* Sum of element (tonne) at T
E6b(e,j)..  sum((m),Z3(m,e,j))=e=Z3b(e,j);

E6c(e,j)..  e_upper(e,j)*Z1b(j)=e=Z3c(e,j);
E6d(e,j)..  e_lower(e,j)*Z1b(j)=e=Z3d(e,j);


E7(e,j).. sum((m),Z3(m,e,j))=l=e_upper(e,j)*Z1b(j);
E8(e,j).. sum((m),Z3(m,e,j))=g=e_lower(e,j)*Z1b(j);

*ELEMENT end


*MASS cont..


*Total material product at T
E3(m,jp).. Z1b('T1')*yieldT1(m,jp) + Z3b('Hv','T2')*yieldT2(m,jp) +
Z3b('Cell','T3')*yieldT3(m,jp) + Z3b('H-cell','T3b')*yieldT3b(m,jp) +
Z3b('Hv','T4')*yieldT4(m,jp)=e=Z2(m,jp);



* Product constraint
E4(m,jp).. (sum((k),TtoD(jp,m,k))+sum((j),TtoT(jp,m,j)))=l=Z2(m,jp);
```

```
*Recycle constraint
E4b(jp,m)..    sum((j),TtoT(jp,m,j))=l=Z2(m,jp)-
sum((k),TtoD(jp,m,k));

* Demand constraint
E5(m,k).. sum((jp),TtoD(jp,m,k))=l=demand_upper(m,k);
E5b(m,k).. sum((jp),TtoD(jp,m,k))=g=demand_lower(m,k);


* MASS end


* Transportation
Parameter
transcost transportation cost $ per tonne per km / 0.0001 /;

Positive Variables
Z4(i,j), Z5(j,jp), Z6(jp,k), Ttranscost;

Table distance_RtoT(i,j)
         T1      T2      T3      T3b     T4
R1       40.00   36.06   89.44   89.44   44.72
R2       31.62   53.85   76.16   76.16   58.31
R3       94.34   58.31   50.00   50.00   50.00
R4       64.03   31.62   64.03   64.03   30.00
R5       50.00   28.28   30.00   30.00   22.36
R6       76.16   64.03   31.62   31.62   58.31     ;

Table distance_TtoT(j,jp)
         T1      T2      T3      T3b     T4
T1       0.00    36.05   80.00   80.00   44.72
T2       36.06   0.00    53.85   53.85   10.00
T3       80.00   53.85   0.00    0.00    44.72
T3b      80.00   53.85   0.00    0.00    44.72
T4       44.72   10.00   44.72   44.72   0.00     ;

Table distance_TtoD(jp,k)
         D1      D2      D3      D4      Export
T1       53.85   36.06   36.06   44.72   94.87
T2       20.00   40.00   0.00    10.00   78.10
T3       36.06   53.85   53.85   44.72   31.62
T3b      36.06   53.85   53.85   44.72   31.62
T4       0.00    41.23   10.00   0.00    70.71 ;

Equations
E9(i,j), E10(j,jp), E11(jp,k), E12;

E9(i,j)..
(sum((m),RtoT(i,m,j))*distance_RtoT(i,j)*transcost)=e=Z4(i,j);
E10(j,jp)..
(sum((m),TtoT(j,m,jp))*distance_TtoT(j,jp)*transcost)=e=Z5(j,jp);
E11(jp,k)..
(sum((m),TtoD(jp,m,k))*distance_TtoD(jp,k)*transcost)=e=Z6(jp,k);
E12..
(sum((i,j),Z4(i,j)))+(sum((j,jp),Z5(j,jp)))+(sum((jp,k),Z6(jp,k)))=e=
Ttranscost;

* TRANSPORTATION end
```

```
* Profit
Parameter
value(m) selling value /Cc 0.1, Pw 0.190, Hn 0.040, Tr 0.030, Cr
0.025, Tw 0.0475, Po 0.396, H2 10, Bio-E 1.57, Gp 0/;

Positive Variable
Z7(m),Total_biomass_cost, Z8(m,jp), Total_Production_Cost,
Z9(m),Total_sell, profit;

Variable
totalprofit;

Equation
E13(m),E13b, E14(m,jp), E14b, E15(m),E15b, E16, obj  ;

* Total resources used in R
E13(m).. sum((i,j),RtoT(i,m,j))=e=Z7(m);

* Total amount used in purchasing raw material
E13b.. sum((m),((Z7(m))*value(m)))=e=Total_biomass_cost;

* Total production cost
E14(m,jp).. Z2(m,jp)*production_cost(m,jp)=e=z8(m,jp);
E14b.. sum((m,jp),z8(m,jp))=e=Total_Production_Cost;

* Total product send to D
E15(m).. sum((jp,k),TtoD(jp,m,k))=e=Z9(m);

* Total sell in D
E15b.. sum((m),((Z9(m))*value(m)))=e=Total_sell;

E16.. Total_sell-Total_Production_Cost-Total_biomass_cost=e=profit;
obj.. Totalprofit=e=profit-Ttranscost ;


Model MarkII /all/;

Solve MarkII using LP maximising Totalprofit;

display RtoT.l, TtoT.l, TtoD.l, totalprofit.l;
```

Case study C

```
* Case study C: BECA approach

set
i resources /R1, R2, R3, R4, R5, R6/
j technology /T1, T2, T3, T3b, T4/
k demand /D1, D2, D3, D4, Export/
m material /Cc, Pw, Hn, Tr, Cr, Tw, Po, H2, Bio-E, Gp/
e element /Ash, FC, VM, MC, HV, Cell, H-cell/

alias (j,jp) ;

Positive variables
RtoT(i,m,j), TtoT(jp,m,j), TtoD(jp,m,k);

Positive Variables
Z1(m,j), Z1b(j), Z2(m,jp), Zz(j) ;

* MASS

* resources availability
Table resource(i,m)
         Cc      Pw      Hn      Tr      Cr      Tw      Po      H2
Bio-E   Gp
R1       3000000 0       0       0       0       0       0       0
0       0
R2       0       2400000 0       0       0       500000  0       0
0       0
R3       0       0       300000  0       0       0       0       0
0       0
R4       0       0       0       950000  0       0       0       0
0       0
R5       0       0       0       0       500000  0       0       0
0       0
R6       0       0       0       0       0       1500000 0       0
0       0;

* technology conversion
Table yieldT1(m,jp)
         T1      T2      T3      T3b     T4
Cc       0       0       0       0       0
Pw       0       0       0       0       0
Hn       0       0       0       0       0
Tr       0       0       0       0       0
Cr       0       0       0       0       0
Tw       0       0       0       0       0
Po       0       0       0       0       0
H2       0.03046 0       0       0       0
Bio-E    0       0       0       0       0
Gp       0       0       0       0       0;

Table yieldT2(m,jp)
         T1      T2      T3      T3b     T4
Cc       0       0       0       0       0
Pw       0       0       0       0       0
Hn       0       0       0       0       0
Tr       0       0       0       0       0
Cr       0       0       0       0       0
Tw       0       0       0       0       0
Po       0       0.68    0       0       0
```

```
H2        0        0        0        0        0
Bio-E     0        0        0        0        0
Gp        0        0.056    0        0        0;

Table yieldT3(m,jp)
          T1       T2       T3       T3b      T4
Cc        0        0        0        0        0
Pw        0        0        0        0        0
Hn        0        0        0        0        0
Tr        0        0        0        0        0
Cr        0        0        0        0        0
Tw        0        0        0        0        0
Po        0        0        0        0        0
H2        0        0        0        0        0
Bio-E     0        0        0.29     0        0
Gp        0        0        0        0        0;

Table yieldT3b(m,jp)
          T1       T2       T3       T3b      T4
Cc        0        0        0        0        0
Pw        0        0        0        0        0
Hn        0        0        0        0        0
Tr        0        0        0        0        0
Cr        0        0        0        0        0
Tw        0        0        0        0        0
Po        0        0        0        0        0
H2        0        0        0        0        0
Bio-E     0        0        0        0.23     0
Gp        0        0        0        0        0;

Table yieldT4(m,jp)
          T1       T2       T3       T3b      T4
Cc        0        0        0        0        0
Pw        0        0        0        0        0
Hn        0        0        0        0        0
Tr        0        0        0        0        0
Cr        0        0        0        0        0
Tw        0        0        0        0        0
Po        0        0        0        0        0.3
H2        0        0        0        0        0
Bio-E     0        0        0        0        0
Gp        0        0        0        0        0;

Table production_cost(m,jp)
          T1       T2       T3       T3b      T4
Cc        0        0        0        0        0
Pw        0        0        0        0        0
Hn        0        0        0        0        0
Tr        0        0        0        0        0
Cr        0        0        0        0        0
Tw        0        0        0        0        0
Po        0        0.019    0        0        0.0152
H2        4.92     0        0        0        0
Bio-E     0        0        0.57     0.57     0
Gp        0        0        0        0        0;

* demand constraint
Table demand_upper(m,k)
          D1       D2       D3       D4       Export
Cc        0        0        0        0        0
Pw        0        0        0        0        0
```

```
Hn       0        0        0        0        0
Tr       0        0        0        0        0
Cr       0        0        0        0        0
Tw       0        0        0        0        0
Po       0        0        50000    70000    9999999999999999
H2       5000     20000    0        0        9999999999999999
Bio-E    15000    13000    0        0        9999999999999999
Gp       0        0        0        0        0        ;

Table demand_lower(m,k)
         D1       D2       D3       D4       Export
Cc       0        0        0        0        0
Pw       0        0        0        0        0
Hn       0        0        0        0        0
Tr       0        0        0        0        0
Cr       0        0        0        0        0
Tw       0        0        0        0        0
Po       0        0        50000    70000    0
H2       5000     20000    0        0        0
Bio-E    15000    13000    0        0        0
Gp       0        0        0        0        0        ;

* Biomass recycle contraint factor (no product is being recycle)
Table TtoTfactor(m,j)
         T1       T2       T3       T3b      T4
Cc       1        1        1        1        1
Pw       1        1        1        1        1
Hn       1        1        1        1        1
Tr       1        1        1        1        1
Cr       1        1        1        1        1
Tw       1        1        1        1        1
Po       0        0        0        0        0
H2       0        0        0        0        0
Bio-E    0        0        0        0        0
Gp       1        1        1        1        1   ;


Equation
E1(i,m), E2(m,j), E3(m,jp), E4(m,jp), E5(m,k),E5b(m,k), E2b(j),
E4b(jp,m);

* Resources constraint
E1(i,m).. sum((j), RtoT(i,m,j))=l=resource(i,m);

* Total material received at T
E2(m,j)..
sum((i),RtoT(i,m,j))+(sum((jp),TtoT(jp,m,j))*TtoTfactor(m,j))=e=Z1(m,
j);

E2b(j)..          sum((m),(Z1(m,j)))=e=Z1b(j);


* ELEMENT
Table element(m,e)
         Ash      FC       VM       MC       HV       Cell     H-cell
Cc       0.029    0.174    0.727    0.07     0.192    0.30     0.15
Pw       0.016    0.19     0.713    0.08     0.212    0.40     0.200
Hn       0.017    0.18     0.735    0.068    0.194    0.382    0.121
Tr       0.037    0.165    0.723    0.075    0.19     0.24     0.17
Cr       0.15     0.067    0.663    0.12     0.158    0.311    0.054
Tw       0.049    0.0      0.803    0.148    0.196    0.38     0.25
```

```
Po       0        0        0        0        0        0        0
H2       0        0        0        0        0        0        0
Bio-E    0        0        0        0        0        0        0
Gp       0.081    0.844    0.065    0.01     0.299    0        0  ;

Table e_upper(e,j)
         T1       T2       T3       T3b      T4
Ash      0.03045 0.0168   1        1        1
FC       0.1827   0.1995   1        1        1
VM       0.76335 0.7518   1        1        1
MC       0.0735   0.084    1        1        0.5
HV       0.2016   0.2226   1        1        1
Cell     0.315    0.42     1        1        1
H-cell   0.1575   0.21     1        1        1;

Table e_lower(e,j)
         T1       T2       T3       T3b      T4
Ash      0.02755 0.0152   0        0        0
FC       0.1653   0.1805   0        0        0
VM       0.69065 0.6802   0        0        0
MC       0.0665   0.076    0        0        0
HV       0.1824   0.2014   0        0        0
Cell     0.285    0.38     0        0        0
H-cell   0.1425   0.19     0        0        0     ;


Positive Variable
Z3(m,e,j),Z3b(e,j),Z3c(e,j),Z3d(e,j);

Equation
E6(m,e,j), E6b(e,j), E7(e,j), E8(e,j),E6c(e,j),E6d(e,j);

* Element received at T
E6(m,e,j).. Z1(m,j)*element(m,e)=e=Z3(m,e,j) ;

* Sum of element (tonne) at T
E6b(e,j)..  sum((m),Z3(m,e,j))=e=Z3b(e,j);

E6c(e,j)..  e_upper(e,j)*Z1b(j)=e=Z3c(e,j);
E6d(e,j)..  e_lower(e,j)*Z1b(j)=e=Z3d(e,j);


E7(e,j).. sum((m),Z3(m,e,j))=l=e_upper(e,j)*Z1b(j);
E8(e,j).. sum((m),Z3(m,e,j))=g=e_lower(e,j)*Z1b(j);

*ELEMENT end


*MASS cont..


*Total material product at T
E3(m,jp).. Z1b('T1')*yieldT1(m,jp) + Z3b('Hv','T2')*yieldT2(m,jp) +
Z3b('Cell','T3')*yieldT3(m,jp) + Z3b('H-cell','T3b')*yieldT3b(m,jp) +
Z3b('Hv','T4')*yieldT4(m,jp)=e=Z2(m,jp);

* Product constraint
E4(m,jp).. (sum((k),TtoD(jp,m,k))+sum((j),TtoT(jp,m,j)))=l=Z2(m,jp);

*Recycle constraint
```

```
E4b(jp,m)..     sum((j),TtoT(jp,m,j))=l=Z2(m,jp)-
sum((k),TtoD(jp,m,k));

* Demand constraint
E5(m,k).. sum((jp),TtoD(jp,m,k))=l=demand_upper(m,k);
E5b(m,k).. sum((jp),TtoD(jp,m,k))=g=demand_lower(m,k);


* MASS end


* Transportation
Parameter
transcost transportation cost $ per tonne per km / 0.0001 /;

Positive Variables
Z4(i,j), Z5(j,jp), Z6(jp,k), Ttranscost;

Table distance_RtoT(i,j)
         T1      T2      T3      T3b     T4
R1       40.00   36.06   89.44   89.44   44.72
R2       31.62   53.85   76.16   76.16   58.31
R3       94.34   58.31   50.00   50.00   50.00
R4       64.03   31.62   64.03   64.03   30.00
R5       50.00   28.28   30.00   30.00   22.36
R6       76.16   64.03   31.62   31.62   58.31     ;

Table distance_TtoT(j,jp)
         T1      T2      T3      T3b     T4
T1       0.00    36.05   80.00   80.00   44.72
T2       36.06   0.00    53.85   53.85   10.00
T3       80.00   53.85   0.00    0.00    44.72
T3b      80.00   53.85   0.00    0.00    44.72
T4       44.72   10.00   44.72   44.72   0.00     ;

Table distance_TtoD(jp,k)
         D1      D2      D3      D4      Export
T1       53.85   36.06   36.06   44.72   94.87
T2       20.00   40.00   0.00    10.00   78.10
T3       36.06   53.85   53.85   44.72   31.62
T3b      36.06   53.85   53.85   44.72   31.62
T4       0.00    41.23   10.00   0.00    70.71 ;

Equations
E9(i,j), E10(j,jp), E11(jp,k), E12;

E9(i,j)..
(sum((m),RtoT(i,m,j))*distance_RtoT(i,j)*transcost)=e=Z4(i,j);
E10(j,jp)..
(sum((m),TtoT(j,m,jp))*distance_TtoT(j,jp)*transcost)=e=Z5(j,jp);
E11(jp,k)..
(sum((m),TtoD(jp,m,k))*distance_TtoD(jp,k)*transcost)=e=Z6(jp,k);
E12..
(sum((i,j),Z4(i,j)))+(sum((j,jp),Z5(j,jp)))+(sum((jp,k),Z6(jp,k)))=e=
Ttranscost;

* TRANSPORTATION end


* Profit
Parameter
```

```
value(m) selling value /Cc 0.1, Pw 0.190, Hn 0.040, Tr 0.030, Cr
0.025, Tw 0.0475, Po 0.396, H2 10, Bio-E 1.57, Gp 0/;

Positive Variable
Z7(m),Total_biomass_cost, Z8(m,jp), Total_Production_Cost,
Z9(m),Total_sell, profit;

Variable
totalprofit;

Equation
E13(m),E13b, E14(m,jp), E14b, E15(m),E15b, E16, obj  ;

* Total resources used in R
E13(m).. sum((i,j),RtoT(i,m,j))=e=Z7(m);

* Total amount used in purchasing raw material
E13b.. sum((m),((Z7(m))*value(m)))=e=Total_biomass_cost;

* Total production cost
E14(m,jp).. Z2(m,jp)*production_cost(m,jp)=e=z8(m,jp);
E14b.. sum((m,jp),z8(m,jp))=e=Total_Production_Cost;

* Total product send to D
E15(m).. sum((jp,k),TtoD(jp,m,k))=e=Z9(m);

* Total sell in D
E15b.. sum((m),((Z9(m))*value(m)))=e=Total_sell;

E16.. Total_sell-Total_Production_Cost-Total_biomass_cost=e=profit;
obj.. Totalprofit=e=profit-Ttranscost ;


Model MarkII /all/;

Solve MarkII using LP maximising Totalprofit;

display RtoT.l, TtoT.l, TtoD.l, totalprofit.l;
```

APPENDIX III

Case study (i)

```
* Case study (i)

set
i resources /R1, R2, R3, R4/
j technology /1_T1, 2_T2, 2_T3, 3_T2, 4_T4/
k demand /D1, D2, D3, Export/
m material /PS, OPF, EFB, PKT, PMF, SW, HW, BO, BE, SG, PW/
e element /Cel, Hcel, Lig, Ext, Ash, MC/

alias (j,jp) ;

Positive variables
RtoT(i,m,j), TtoT(jp,m,j), TtoD(jp,m,k);

Positive Variables
MatRecT(m,j), TMatRecT(j), MatGenT(m,jp), Zz(j) ;

* MASS

* resources availability
Table resource(i,m)
         PS      OPF     EFB     PKT     PMF     SW      HW      BO
BE      SG      PW
R1       2500    1500    2000    800     0       0       0       0
0       0       0
R2       1750    2300    2100    0       750     0       0       0
0       0       0
R3       0       0       0       0       0       1500    0       0
0       0       0
R4       0       0       0       0       0       0       1750    0
0       0       0;


* technology conversion
Table yield1_T1(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0.461   0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0;

Table yield2_T2(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
```

```
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       1.94    0       0       0
PW       0       0       0       0       0;

Table yield2_T3(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       10.30   0       0;

Table yield3_T2(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       1.94    0
PW       0       0       0       0       0;

Table yield4_T4(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0.2416
SG       0       0       0       0       0
PW       0       0       0       0       0;

* demand constraint
Table demand_upper(m,k)
         D1      D2      D3      Export
PS       0       0       0       0
OPF      0       0       0       0
EFB      0       0       0       0
PKT      0       0       0       0
PMF      0       0       0       0
SW       0       0       0       0
HW       0       0       0       0
```

```
BO       1000    0       0       99999999990
BE       850     0       0       99999999990
SG       0       600     350     999999999990
PW       0       0       700     0        ;

Table demand_lower(m,k)
         D1      D2      D3      Export
PS       0       0       0       0
OPF      0       0       0       0
EFB      0       0       0       0
PKT      0       0       0       0
PMF      0       0       0       0
SW       0       0       0       0
HW       0       0       0       0
BO       1000    0       0       0
BE       850     0       0       0
SG       0       600     350     0
PW       0       0       700     0        ;

* Biomass recycle contraint factor (no product is being recycle)
Table TtoTfactor(m,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       1       1       1       1       1
OPF      1       1       1       1       1
EFB      1       1       1       1       1
PKT      1       1       1       1       1
PMF      1       1       1       1       1
SW       1       1       1       1       1
HW       1       1       1       1       1
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0   ;


Equation
E1(i,m), E2(m,j), E3(m,jp), E4(m,jp), E5(m,k), E5b(m,k), E2b(j);

* Resources constraint
E1(i,m).. sum((j), RtoT(i,m,j))=l=resource(i,m);

* Total material received at T
E2(m,j)..
sum((i),RtoT(i,m,j))+(sum((jp),TtoT(jp,m,j))*TtoTfactor(m,j))=e=MatRe
cT(m,j);

E2b(j)..         sum((m),(MatRecT(m,j)))=e=TMatRecT(j);



* ELEMENT
Table element(m,e)
         Cel     Hcel    Lig     Ext     Ash     MC
PS       0.277   0.216   0.440   0.02    0.021   0.11
OPF      0.304   0.404   0.217   0.027   0.013   0.16
EFB      0.373   0.146   0.317   0.013   0.067   0.10
PKT      0.345   0.318   0.257   0.027   0.043   0.130
PMF      0.339   0.261   0.277   0.069   0.035   0.131
SW       0.375   0.275   0.285   0.025   0.035   0.14
HW       0.475   0.275   0.225   0.025   0.035   0.14
BO       0       0       0       0       0       0
```

```
BE       0       0       0       0       0       0
SG       0       0       0       0       0       0
PW       0       0       0       0       0       0         ;

Table e_upper(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.327   0.354   0.354   0.354   0.423
Hcel     0.266   0.454   0.454   0.454   0.196
Lig      0.49    0.267   0.267   0.267   0.367
Ext      0.07    0.077   0.077   0.077   0.063
Ash      0.071   0.063   0.063   0.063   0.117
MC       0.16    0.21    0.21    0.21    0.15   ;

Table e_lower(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.227   0.254   0.254   0.254   0.323
Hcel     0.166   0.354   0.354   0.354   0.096
Lig      0.39    0.167   0.167   0.167   0.267
Ext      0       0       0       0       0
Ash      0       0       0       0       0.017
MC       0.06    0.11    0.11    0.11    0.05        ;


Positive Variable
EleRecT(m,e,j),Z3b(e,j);

Equation
E6(m,e,j), E6b(e,j), E7(e,j), E8(e,j);

* Element received at T
E6(m,e,j).. MatRecT(m,j)*element(m,e)=e=EleRecT(m,e,j) ;

* Sum of element (tonne) at T
E6b(e,j)..  sum((m),EleRecT(m,e,j))=e=Z3b(e,j);

E7(e,j).. sum((m),EleRecT(m,e,j))=l=e_upper(e,j)*TMatRecT(j);
E8(e,j).. sum((m),EleRecT(m,e,j))=g=e_lower(e,j)*TMatRecT(j);

*ELEMENT end


*MASS cont..


*Total material product at T
E3(m,jp).. TMatRecT('1_T1')*yield1_T1(m,jp) +
TMatRecT('2_T2')*yield2_T2(m,jp) + TMatRecT('2_T3')*yield2_T3(m,jp) +
TMatRecT('3_T2')*yield3_T2(m,jp) +
TMatRecT('4_T4')*yield4_T4(m,jp)=e=MatGenT(m,jp);

* Product constraint
E4(m,jp)..
(sum((k),TtoD(jp,m,k))+sum((j),TtoT(jp,m,j)))=l=MatGenT(m,jp);

* Demand constraint
E5(m,k).. sum((jp),TtoD(jp,m,k))=l=demand_upper(m,k);
E5b(m,k).. sum((jp),TtoD(jp,m,k))=g=demand_lower(m,k);


* MASS end
```

```
* Transportation
Parameter
transcost transportation cost RM per tonne per km / 0.25 /;

Positive Variables
Cost_RtoT(i,j), Cost_TtoT(j,jp), Cost_TtoD(jp,k), Ttranscost;

Table distance_RtoT(i,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
R1       600.0   360.6   360.6   854.4   565.7
R2       608.3   583.1   583.1   447.2   360.6
R3       1063.0  583.1   583.1   400.0   640.3
R4       721.1   223.6   223.6   500.0   400.0     ;

Table distance_TtoT(j,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
1_T1     0       500.0   500.0   584.4   447.2
2_T2     500.0   0       0       509.9   223.6
2_T3     500.0   0       0       509.9   223.6
3_T2     854.4   509.9   509.0   0       412.3
4_T4     447.2   223.6   223.6   412.3   0     ;

Table distance_TtoD(jp,k)
         D1      D2      D3      Export
1_T1     640.3   300.0   500.0   905.5
2_T2     200.0   400.0   0       781.0
2_T3     200.0   400.0   0       781.0
3_T2     316.2   583.1   509.9   412.3
4_T4     223.6   223.6   223.6   583.1  ;

Equations
E9(i,j), E10(j,jp), E11(jp,k), E12;

E9(i,j)..
(sum((m),RtoT(i,m,j))*distance_RtoT(i,j)*transcost)=e=Cost_RtoT(i,j);
E10(j,jp)..
(sum((m),TtoT(j,m,jp))*distance_TtoT(j,jp)*transcost)=e=Cost_TtoT(j,j
p);
E11(jp,k)..
(sum((m),TtoD(jp,m,k))*distance_TtoD(jp,k)*transcost)=e=Cost_TtoD(jp,
k);
E12..
(sum((i,j),Cost_RtoT(i,j)))+(sum((j,jp),Cost_TtoT(j,jp)))+(sum((jp,k)
,Cost_TtoD(jp,k)))=e=Ttranscost;

* TRANSPORTATION end


* Profit
Parameter
value(m) selling value /PS 120, OPF 110, EFB 105, PKT 65, PMF 75, SW
50, HW 85, BO 300, BE 450, SG 325, PW 260/;

Positive Variable
Z7(m),Z7b, Z8(m), Z9(m),Z9b, profit;

Variable
totalprofit;

Equation
```

```
E13(m),E13b, E15(m),E15b, E16, obj  ;

* Total resources used in R
E13(m).. sum((i,j),RtoT(i,m,j))=e=Z7(m);

* Total amount used in purchasing raw material
E13b.. sum((m),((Z7(m))*value(m)))=e=Z7b;

* Total product send to D
E15(m).. sum((jp,k),TtoD(jp,m,k))=e=Z9(m);

* Total sell in D
E15b.. sum((m),((Z9(m))*value(m)))=e=Z9b;

E16.. Z9b-Z7b=e=profit;
obj.. Totalprofit=e=profit-Ttranscost ;


Model MarkII /all/;

Solve MarkII using LP maximising Totalprofit;

display RtoT.l, TtoT.l, TtoD.l, Totalprofit.l;
```

Case study (ii)

```
* Case study (ii)

set
i resources /R1, R2, R3, R4/
j technology /1_T1, 2_T2, 2_T3, 3_T2, 4_T4/
k demand /D1, D2, D3, Export/
m material /PS, OPF, EFB, PKT, PMF, SW, HW, BO, BE, SG, PW/
e element /Cel, Hcel, Lig, Ext, Ash, MC/

alias (j,jp) ;

Positive variables
RtoT(i,m,j), TtoT(jp,m,j), TtoD(jp,m,k);

Positive Variables
MatRecT(m,j), TMatRecT(j), MatGenT(m,jp), Zz(j) ;

* MASS

* resources availability
Table resource(i,m)
         PS      OPF     EFB     PKT     PMF     SW      HW      BO
BE      SG      PW
R1       1250    750     1000    400     0       0       0       0
0       0       0
R2       1750    2300    2100    0       750     0       0       0
0       0       0
R3       0       0       0       0       0       1500    0       0
0       0       0
R4       0       0       0       0       0       0       1750    0
0       0       0;


* technology conversion
Table yield1_T1(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0.461   0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0;

Table yield2_T2(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0
```

```
SG       0       1.94    0       0       0
PW       0       0       0       0       0;

Table yield2_T3(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       10.30   0       0;

Table yield3_T2(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       1.94    0
PW       0       0       0       0       0;

Table yield4_T4(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0.2416
SG       0       0       0       0       0
PW       0       0       0       0       0;

* demand constraint
Table demand_upper(m,k)
         D1      D2      D3      Export
PS       0       0       0       0
OPF      0       0       0       0
EFB      0       0       0       0
PKT      0       0       0       0
PMF      0       0       0       0
SW       0       0       0       0
HW       0       0       0       0
BO       1000    0       0       99999999990
BE       850     0       0       99999999990
SG       0       600     350     999999999990
PW       0       0       700     0          ;

Table demand_lower(m,k)
```

```
         D1      D2      D3      Export
PS       0       0       0       0
OPF      0       0       0       0
EFB      0       0       0       0
PKT      0       0       0       0
PMF      0       0       0       0
SW       0       0       0       0
HW       0       0       0       0
BO       1000    0       0       0
BE       850     0       0       0
SG       0       600     350     0
PW       0       0       700     0        ;

* Biomass recycle contraint factor (no product is being recycle)
Table TtoTfactor(m,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       1       1       1       1       1
OPF      1       1       1       1       1
EFB      1       1       1       1       1
PKT      1       1       1       1       1
PMF      1       1       1       1       1
SW       1       1       1       1       1
HW       1       1       1       1       1
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0   ;


Equation
E1(i,m), E2(m,j), E3(m,jp), E4(m,jp), E5(m,k), E5b(m,k), E2b(j);

* Resources constraint
E1(i,m).. sum((j), RtoT(i,m,j))=l=resource(i,m);

* Total material received at T
E2(m,j)..
sum((i),RtoT(i,m,j))+(sum((jp),TtoT(jp,m,j))*TtoTfactor(m,j))=e=MatRe
cT(m,j);

E2b(j)..         sum((m),(MatRecT(m,j)))=e=TMatRecT(j);

* ELEMENT
Table element(m,e)
         Cel     Hcel    Lig     Ext     Ash     MC
PS       0.277   0.216   0.440   0.02    0.021   0.11
OPF      0.304   0.404   0.217   0.027   0.013   0.16
EFB      0.373   0.146   0.317   0.013   0.067   0.10
PKT      0.345   0.318   0.257   0.027   0.043   0.130
PMF      0.339   0.261   0.277   0.069   0.035   0.131
SW       0.375   0.275   0.285   0.025   0.035   0.14
HW       0.475   0.275   0.225   0.025   0.035   0.14
BO       0       0       0       0       0       0
BE       0       0       0       0       0       0
SG       0       0       0       0       0       0
PW       0       0       0       0       0       0        ;

Table e_upper(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.327   0.354   0.354   0.354   0.423
Hcel     0.266   0.454   0.454   0.454   0.196
```

```
Lig      0.49    0.267   0.267   0.267   0.367
Ext      0.07    0.077   0.077   0.077   0.063
Ash      0.071   0.063   0.063   0.063   0.117
MC       0.16    0.21    0.21    0.21    0.15   ;

Table e_lower(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.227   0.254   0.254   0.254   0.323
Hcel     0.166   0.354   0.354   0.354   0.096
Lig      0.39    0.167   0.167   0.167   0.267
Ext      0       0       0       0       0
Ash      0       0       0       0       0.017
MC       0.06    0.11    0.11    0.11    0.05        ;


Positive Variable
EleRecT(m,e,j),Z3b(e,j);

Equation
E6(m,e,j), E6b(e,j), E7(e,j), E8(e,j);

* Element received at T
E6(m,e,j).. MatRecT(m,j)*element(m,e)=e=EleRecT(m,e,j) ;

* Sum of element (tonne) at T
E6b(e,j)..  sum((m),EleRecT(m,e,j))=e=Z3b(e,j);

E7(e,j).. sum((m),EleRecT(m,e,j))=l=e_upper(e,j)*TMatRecT(j);
E8(e,j).. sum((m),EleRecT(m,e,j))=g=e_lower(e,j)*TMatRecT(j);

*ELEMENT end


*MASS cont..


*Total material product at T
E3(m,jp).. TMatRecT('1_T1')*yield1_T1(m,jp) +
TMatRecT('2_T2')*yield2_T2(m,jp) + TMatRecT('2_T3')*yield2_T3(m,jp) +
TMatRecT('3_T2')*yield3_T2(m,jp) +
TMatRecT('4_T4')*yield4_T4(m,jp)=e=MatGenT(m,jp);

* Product constraint
E4(m,jp)..
(sum((k),TtoD(jp,m,k))+sum((j),TtoT(jp,m,j)))=l=MatGenT(m,jp);

* Demand constraint
E5(m,k).. sum((jp),TtoD(jp,m,k))=l=demand_upper(m,k);
E5b(m,k).. sum((jp),TtoD(jp,m,k))=g=demand_lower(m,k);


* MASS end


* Transportation
Parameter
transcost transportation cost RM per tonne per km / 0.25 /;

Positive Variables
Cost_RtoT(i,j), Cost_TtoT(j,jp), Cost_TtoD(jp,k), Ttranscost;
```

```
Table distance_RtoT(i,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
R1       600.0   360.6   360.6   854.4   565.7
R2       608.3   583.1   583.1   447.2   360.6
R3       1063.0  583.1   583.1   400.0   640.3
R4       721.1   223.6   223.6   500.0   400.0     ;

Table distance_TtoT(j,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
1_T1     0       500.0   500.0   584.4   447.2
2_T2     500.0   0       0       509.9   223.6
2_T3     500.0   0       0       509.9   223.6
3_T2     854.4   509.9   509.0   0       412.3
4_T4     447.2   223.6   223.6   412.3   0     ;

Table distance_TtoD(jp,k)
         D1      D2      D3      Export
1_T1     640.3   300.0   500.0   905.5
2_T2     200.0   400.0   0       781.0
2_T3     200.0   400.0   0       781.0
3_T2     316.2   583.1   509.9   412.3
4_T4     223.6   223.6   223.6   583.1  ;

Equations
E9(i,j), E10(j,jp), E11(jp,k), E12;

E9(i,j)..
(sum((m),RtoT(i,m,j))*distance_RtoT(i,j)*transcost)=e=Cost_RtoT(i,j);
E10(j,jp)..
(sum((m),TtoT(j,m,jp))*distance_TtoT(j,jp)*transcost)=e=Cost_TtoT(j,j
p);
E11(jp,k)..
(sum((m),TtoD(jp,m,k))*distance_TtoD(jp,k)*transcost)=e=Cost_TtoD(jp,
k);
E12..
(sum((i,j),Cost_RtoT(i,j)))+(sum((j,jp),Cost_TtoT(j,jp)))+(sum((jp,k)
,Cost_TtoD(jp,k)))=e=Ttranscost;

* TRANSPORTATION end

* Profit
Parameter
value(m) selling value /PS 120, OPF 110, EFB 105, PKT 65, PMF 75, SW
50, HW 85, BO 300, BE 450, SG 325, PW 260/;

Positive Variable
Z7(m),Z7b, Z8(m), Z9(m),Z9b, profit;

Variable
totalprofit;

Equation
E13(m),E13b, E15(m),E15b, E16, obj  ;

* Total resources used in R
E13(m).. sum((i,j),RtoT(i,m,j))=e=Z7(m);

* Total amount used in purchasing raw material
E13b.. sum((m),((Z7(m))*value(m)))=e=Z7b;

* Total product send to D
```

```
E15(m).. sum((jp,k),TtoD(jp,m,k))=e=Z9(m);

* Total sell in D
E15b.. sum((m),((Z9(m))*value(m)))=e=Z9b;

E16.. Z9b-Z7b=e=profit;
obj.. Totalprofit=e=profit-Ttranscost ;


Model MarkII /all/;

Solve MarkII using LP maximising Totalprofit;

display RtoT.l, TtoT.l, TtoD.l, Totalprofit.l;
```

Case study (iii)

```
* Case study (iii)

set
i resources /R1, R2, R3, R4/
j technology /1_T1, 2_T2, 2_T3, 3_T2, 4_T4/
k demand /D1, D2, D3, Export/
m material /PS, OPF, EFB, PKT, PMF, SW, HW, BO, BE, SG, PW/
e element /Cel, Hcel, Lig, Ext, Ash, MC/

alias (j,jp) ;

Positive variables
RtoT(i,m,j), TtoT(jp,m,j), TtoD(jp,m,k);

Positive Variables
MatRecT(m,j), TMatRecT(j), MatGenT(m,jp), Zz(j) ;

* MASS

* resources availability
Table resource(i,m)
         PS      OPF     EFB     PKT     PMF     SW      HW      BO
BE      SG      PW
R1       2500    1500    2000    800     0       0       0       0
0       0       0
R2       8750    1150    1050    0       375     0       0       0
0       0       0
R3       0       0       0       0       0       1500    0       0
0       0       0
R4       0       0       0       0       0       0       1750    0
0       0       0;


* technology conversion
Table yield1_T1(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0.461   0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0;

Table yield2_T2(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0
```

```
SG        0        1.94     0        0        0
PW        0        0        0        0        0;

Table yield2_T3(m,jp)
          1_T1     2_T2     2_T3     3_T2     4_T4
PS        0        0        0        0        0
OPF       0        0        0        0        0
EFB       0        0        0        0        0
PKT       0        0        0        0        0
PMF       0        0        0        0        0
SW        0        0        0        0        0
HW        0        0        0        0        0
BO        0        0        0        0        0
BE        0        0        0        0        0
SG        0        0        0        0        0
PW        0        0        10.30    0        0;

Table yield3_T2(m,jp)
          1_T1     2_T2     2_T3     3_T2     4_T4
PS        0        0        0        0        0
OPF       0        0        0        0        0
EFB       0        0        0        0        0
PKT       0        0        0        0        0
PMF       0        0        0        0        0
SW        0        0        0        0        0
HW        0        0        0        0        0
BO        0        0        0        0        0
BE        0        0        0        0        0
SG        0        0        0        1.94     0
PW        0        0        0        0        0;

Table yield4_T4(m,jp)
          1_T1     2_T2     2_T3     3_T2     4_T4
PS        0        0        0        0        0
OPF       0        0        0        0        0
EFB       0        0        0        0        0
PKT       0        0        0        0        0
PMF       0        0        0        0        0
SW        0        0        0        0        0
HW        0        0        0        0        0
BO        0        0        0        0        0
BE        0        0        0        0        0.2416
SG        0        0        0        0        0
PW        0        0        0        0        0;

* demand constraint
Table demand_upper(m,k)
          D1       D2       D3       Export
PS        0        0        0        0
OPF       0        0        0        0
EFB       0        0        0        0
PKT       0        0        0        0
PMF       0        0        0        0
SW        0        0        0        0
HW        0        0        0        0
BO        1000     0        0        99999999990
BE        850      0        0        99999999990
SG        0        600      350      999999999990
PW        0        0        700      0          ;

Table demand_lower(m,k)
```

```
         D1      D2      D3      Export
PS       0       0       0       0
OPF      0       0       0       0
EFB      0       0       0       0
PKT      0       0       0       0
PMF      0       0       0       0
SW       0       0       0       0
HW       0       0       0       0
BO       1000    0       0       0
BE       850     0       0       0
SG       0       600     350     0
PW       0       0       700     0        ;

* Biomass recycle contraint factor (no product is being recycle)
Table TtoTfactor(m,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       1       1       1       1       1
OPF      1       1       1       1       1
EFB      1       1       1       1       1
PKT      1       1       1       1       1
PMF      1       1       1       1       1
SW       1       1       1       1       1
HW       1       1       1       1       1
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0   ;


Equation
E1(i,m), E2(m,j), E3(m,jp), E4(m,jp), E5(m,k), E5b(m,k), E2b(j);

* Resources constraint
E1(i,m).. sum((j), RtoT(i,m,j))=l=resource(i,m);

* Total material received at T
E2(m,j)..
sum((i),RtoT(i,m,j))+(sum((jp),TtoT(jp,m,j))*TtoTfactor(m,j))=e=MatRe
cT(m,j);

E2b(j)..         sum((m),(MatRecT(m,j)))=e=TMatRecT(j);


* ELEMENT
Table element(m,e)
         Cel     Hcel    Lig     Ext     Ash     MC
PS       0.277   0.216   0.440   0.02    0.021   0.11
OPF      0.304   0.404   0.217   0.027   0.013   0.16
EFB      0.373   0.146   0.317   0.013   0.067   0.10
PKT      0.345   0.318   0.257   0.027   0.043   0.130
PMF      0.339   0.261   0.277   0.069   0.035   0.131
SW       0.375   0.275   0.285   0.025   0.035   0.14
HW       0.475   0.275   0.225   0.025   0.035   0.14
BO       0       0       0       0       0       0
BE       0       0       0       0       0       0
SG       0       0       0       0       0       0
PW       0       0       0       0       0       0       ;

Table e_upper(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.327   0.354   0.354   0.354   0.423
```

```
Hcel      0.266   0.454   0.454   0.454   0.196
Lig       0.49    0.267   0.267   0.267   0.367
Ext       0.07    0.077   0.077   0.077   0.063
Ash       0.071   0.063   0.063   0.063   0.117
MC        0.16    0.21    0.21    0.21    0.15   ;

Table e_lower(e,j)
          1_T1    2_T2    2_T3    3_T2    4_T4
Cel       0.227   0.254   0.254   0.254   0.323
Hcel      0.166   0.354   0.354   0.354   0.096
Lig       0.39    0.167   0.167   0.167   0.267
Ext       0       0       0       0       0
Ash       0       0       0       0       0.017
MC        0.06    0.11    0.11    0.11    0.05        ;


Positive Variable
EleRecT(m,e,j),Z3b(e,j);

Equation
E6(m,e,j), E6b(e,j), E7(e,j), E8(e,j);

* Element received at T
E6(m,e,j).. MatRecT(m,j)*element(m,e)=e=EleRecT(m,e,j) ;

* Sum of element (tonne) at T
E6b(e,j)..  sum((m),EleRecT(m,e,j))=e=Z3b(e,j);

E7(e,j).. sum((m),EleRecT(m,e,j))=l=e_upper(e,j)*TMatRecT(j);
E8(e,j).. sum((m),EleRecT(m,e,j))=g=e_lower(e,j)*TMatRecT(j);

*ELEMENT end


*MASS cont..


*Total material product at T
E3(m,jp).. TMatRecT('1_T1')*yield1_T1(m,jp) +
TMatRecT('2_T2')*yield2_T2(m,jp) + TMatRecT('2_T3')*yield2_T3(m,jp) +
TMatRecT('3_T2')*yield3_T2(m,jp) +
TMatRecT('4_T4')*yield4_T4(m,jp)=e=MatGenT(m,jp);

* Product constraint
E4(m,jp)..
(sum((k),TtoD(jp,m,k))+sum((j),TtoT(jp,m,j)))=l=MatGenT(m,jp);

* Demand constraint
E5(m,k).. sum((jp),TtoD(jp,m,k))=l=demand_upper(m,k);
E5b(m,k).. sum((jp),TtoD(jp,m,k))=g=demand_lower(m,k);


* MASS end


* Transportation
Parameter
transcost transportation cost RM per tonne per km / 0.25 /;

Positive Variables
Cost_RtoT(i,j), Cost_TtoT(j,jp), Cost_TtoD(jp,k), Ttranscost;
```

```
Table distance_RtoT(i,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
R1       600.0   360.6   360.6   854.4   565.7
R2       608.3   583.1   583.1   447.2   360.6
R3       1063.0  583.1   583.1   400.0   640.3
R4       721.1   223.6   223.6   500.0   400.0     ;

Table distance_TtoT(j,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
1_T1     0       500.0   500.0   584.4   447.2
2_T2     500.0   0       0       509.9   223.6
2_T3     500.0   0       0       509.9   223.6
3_T2     854.4   509.9   509.0   0       412.3
4_T4     447.2   223.6   223.6   412.3   0     ;

Table distance_TtoD(jp,k)
         D1      D2      D3      Export
1_T1     640.3   300.0   500.0   905.5
2_T2     200.0   400.0   0       781.0
2_T3     200.0   400.0   0       781.0
3_T2     316.2   583.1   509.9   412.3
4_T4     223.6   223.6   223.6   583.1  ;

Equations
E9(i,j), E10(j,jp), E11(jp,k), E12;

E9(i,j)..
(sum((m),RtoT(i,m,j))*distance_RtoT(i,j)*transcost)=e=Cost_RtoT(i,j);
E10(j,jp)..
(sum((m),TtoT(j,m,jp))*distance_TtoT(j,jp)*transcost)=e=Cost_TtoT(j,j
p);
E11(jp,k)..
(sum((m),TtoD(jp,m,k))*distance_TtoD(jp,k)*transcost)=e=Cost_TtoD(jp,
k);
E12..
(sum((i,j),Cost_RtoT(i,j)))+(sum((j,jp),Cost_TtoT(j,jp)))+(sum((jp,k)
,Cost_TtoD(jp,k)))=e=Ttranscost;

* TRANSPORTATION end

* Profit
Parameter
value(m) selling value /PS 120, OPF 110, EFB 105, PKT 65, PMF 75, SW
50, HW 85, BO 300, BE 450, SG 325, PW 260/;

Positive Variable
Z7(m),Z7b, Z8(m), Z9(m),Z9b, profit;

Variable
totalprofit;

Equation
E13(m),E13b, E15(m),E15b, E16, obj  ;

* Total resources used in R
E13(m).. sum((i,j),RtoT(i,m,j))=e=Z7(m);

* Total amount used in purchasing raw material
E13b.. sum((m),((Z7(m))*value(m)))=e=Z7b;
```

```
* Total product send to D
E15(m).. sum((jp,k),TtoD(jp,m,k))=e=Z9(m);

* Total sell in D
E15b.. sum((m),((Z9(m))*value(m)))=e=Z9b;

E16.. Z9b-Z7b=e=profit;
obj.. Totalprofit=e=profit-Ttranscost ;


Model MarkII /all/;

Solve MarkII using LP maximising Totalprofit;

display RtoT.l, TtoT.l, TtoD.l, Totalprofit.l;
```

Case study (iv)

```
* Case study (iv)

set
i resources /R1, R2, R3, R4/
j technology /1_T1, 2_T2, 2_T3, 3_T2, 4_T4/
k demand /D1, D2, D3, Export/
m material /PS, OPF, EFB, PKT, PMF, SW, HW, BO, BE, SG, PW/
e element /Cel, Hcel, Lig, Ext, Ash, MC/

alias (j,jp) ;

Positive variables
RtoT(i,m,j), TtoT(jp,m,j), TtoD(jp,m,k);

Positive Variables
MatRecT(m,j), TMatRecT(j), MatGenT(m,jp), Zz(j) ;

* MASS

* resources availability
Table resource(i,m)
         PS      OPF     EFB     PKT     PMF     SW      HW      BO
BE      SG      PW
R1       1250    750     1000    400     0       0       0       0
0       0       0
R2       875     1150    1050    0       375     0       0       0
0       0       0
R3       0       0       0       0       0       1500    0       0
0       0       0
R4       0       0       0       0       0       0       1750    0
0       0       0;


* technology conversion
Table yield1_T1(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0.461   0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0;

Table yield2_T2(m,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       0       0       0       0       0
OPF      0       0       0       0       0
EFB      0       0       0       0       0
PKT      0       0       0       0       0
PMF      0       0       0       0       0
SW       0       0       0       0       0
HW       0       0       0       0       0
BO       0       0       0       0       0
BE       0       0       0       0       0
```

```
SG       0        1.94     0        0        0
PW       0        0        0        0        0;

Table yield2_T3(m,jp)
         1_T1     2_T2     2_T3     3_T2     4_T4
PS       0        0        0        0        0
OPF      0        0        0        0        0
EFB      0        0        0        0        0
PKT      0        0        0        0        0
PMF      0        0        0        0        0
SW       0        0        0        0        0
HW       0        0        0        0        0
BO       0        0        0        0        0
BE       0        0        0        0        0
SG       0        0        0        0        0
PW       0        0        10.30    0        0;

Table yield3_T2(m,jp)
         1_T1     2_T2     2_T3     3_T2     4_T4
PS       0        0        0        0        0
OPF      0        0        0        0        0
EFB      0        0        0        0        0
PKT      0        0        0        0        0
PMF      0        0        0        0        0
SW       0        0        0        0        0
HW       0        0        0        0        0
BO       0        0        0        0        0
BE       0        0        0        0        0
SG       0        0        0        1.94     0
PW       0        0        0        0        0;

Table yield4_T4(m,jp)
         1_T1     2_T2     2_T3     3_T2     4_T4
PS       0        0        0        0        0
OPF      0        0        0        0        0
EFB      0        0        0        0        0
PKT      0        0        0        0        0
PMF      0        0        0        0        0
SW       0        0        0        0        0
HW       0        0        0        0        0
BO       0        0        0        0        0
BE       0        0        0        0        0.2416
SG       0        0        0        0        0
PW       0        0        0        0        0;

* demand constraint
Table demand_upper(m,k)
         D1       D2       D3       Export
PS       0        0        0        0
OPF      0        0        0        0
EFB      0        0        0        0
PKT      0        0        0        0
PMF      0        0        0        0
SW       0        0        0        0
HW       0        0        0        0
BO       1000     0        0        99999999990
BE       850      0        0        99999999990
SG       0        600      350      999999999990
PW       0        0        700      0          ;

Table demand_lower(m,k)
```

```
         D1      D2      D3      Export
PS       0       0       0       0
OPF      0       0       0       0
EFB      0       0       0       0
PKT      0       0       0       0
PMF      0       0       0       0
SW       0       0       0       0
HW       0       0       0       0
BO       1000    0       0       0
BE       850     0       0       0
SG       0       600     350     0
PW       0       0       700     0        ;

* Biomass recycle contraint factor (no product is being recycle)
Table TtoTfactor(m,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
PS       1       1       1       1       1
OPF      1       1       1       1       1
EFB      1       1       1       1       1
PKT      1       1       1       1       1
PMF      1       1       1       1       1
SW       1       1       1       1       1
HW       1       1       1       1       1
BO       0       0       0       0       0
BE       0       0       0       0       0
SG       0       0       0       0       0
PW       0       0       0       0       0   ;


Equation
E1(i,m), E2(m,j), E3(m,jp), E4(m,jp), E5(m,k), E5b(m,k), E2b(j);

* Resources constraint
E1(i,m).. sum((j), RtoT(i,m,j))=l=resource(i,m);

* Total material received at T
E2(m,j)..
sum((i),RtoT(i,m,j))+(sum((jp),TtoT(jp,m,j))*TtoTfactor(m,j))=e=MatRe
cT(m,j);

E2b(j)..         sum((m),(MatRecT(m,j)))=e=TMatRecT(j);


* ELEMENT
Table element(m,e)
         Cel     Hcel    Lig     Ext     Ash     MC
PS       0.277   0.216   0.440   0.02    0.021   0.11
OPF      0.304   0.404   0.217   0.027   0.013   0.16
EFB      0.373   0.146   0.317   0.013   0.067   0.10
PKT      0.345   0.318   0.257   0.027   0.043   0.130
PMF      0.339   0.261   0.277   0.069   0.035   0.131
SW       0.375   0.275   0.285   0.025   0.035   0.14
HW       0.475   0.275   0.225   0.025   0.035   0.14
BO       0       0       0       0       0       0
BE       0       0       0       0       0       0
SG       0       0       0       0       0       0
PW       0       0       0       0       0       0        ;

Table e_upper(e,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
Cel      0.327   0.354   0.354   0.354   0.423
```

```
Hcel      0.266   0.454   0.454   0.454   0.196
Lig       0.49    0.267   0.267   0.267   0.367
Ext       0.07    0.077   0.077   0.077   0.063
Ash       0.071   0.063   0.063   0.063   0.117
MC        0.16    0.21    0.21    0.21    0.15   ;

Table e_lower(e,j)
          1_T1    2_T2    2_T3    3_T2    4_T4
Cel       0.227   0.254   0.254   0.254   0.323
Hcel      0.166   0.354   0.354   0.354   0.096
Lig       0.39    0.167   0.167   0.167   0.267
Ext       0       0       0       0       0
Ash       0       0       0       0       0.017
MC        0.06    0.11    0.11    0.11    0.05        ;


Positive Variable
EleRecT(m,e,j),Z3b(e,j);

Equation
E6(m,e,j), E6b(e,j), E7(e,j), E8(e,j);

* Element received at T
E6(m,e,j).. MatRecT(m,j)*element(m,e)=e=EleRecT(m,e,j) ;

* Sum of element (tonne) at T
E6b(e,j)..  sum((m),EleRecT(m,e,j))=e=Z3b(e,j);

E7(e,j).. sum((m),EleRecT(m,e,j))=l=e_upper(e,j)*TMatRecT(j);
E8(e,j).. sum((m),EleRecT(m,e,j))=g=e_lower(e,j)*TMatRecT(j);

*ELEMENT end


*MASS cont..


*Total material product at T
E3(m,jp).. TMatRecT('1_T1')*yield1_T1(m,jp) +
TMatRecT('2_T2')*yield2_T2(m,jp) + TMatRecT('2_T3')*yield2_T3(m,jp) +
TMatRecT('3_T2')*yield3_T2(m,jp) +
TMatRecT('4_T4')*yield4_T4(m,jp)=e=MatGenT(m,jp);

* Product constraint
E4(m,jp)..
(sum((k),TtoD(jp,m,k))+sum((j),TtoT(jp,m,j)))=l=MatGenT(m,jp);

* Demand constraint
E5(m,k).. sum((jp),TtoD(jp,m,k))=l=demand_upper(m,k);
E5b(m,k).. sum((jp),TtoD(jp,m,k))=g=demand_lower(m,k);


* MASS end


* Transportation
Parameter
transcost transportation cost RM per tonne per km / 0.25 /;

Positive Variables
Cost_RtoT(i,j), Cost_TtoT(j,jp), Cost_TtoD(jp,k), Ttranscost;
```

```
Table distance_RtoT(i,j)
         1_T1    2_T2    2_T3    3_T2    4_T4
R1       600.0   360.6   360.6   854.4   565.7
R2       608.3   583.1   583.1   447.2   360.6
R3       1063.0  583.1   583.1   400.0   640.3
R4       721.1   223.6   223.6   500.0   400.0     ;

Table distance_TtoT(j,jp)
         1_T1    2_T2    2_T3    3_T2    4_T4
1_T1     0       500.0   500.0   584.4   447.2
2_T2     500.0   0       0       509.9   223.6
2_T3     500.0   0       0       509.9   223.6
3_T2     854.4   509.9   509.0   0       412.3
4_T4     447.2   223.6   223.6   412.3   0     ;

Table distance_TtoD(jp,k)
         D1      D2      D3      Export
1_T1     640.3   300.0   500.0   905.5
2_T2     200.0   400.0   0       781.0
2_T3     200.0   400.0   0       781.0
3_T2     316.2   583.1   509.9   412.3
4_T4     223.6   223.6   223.6   583.1  ;

Equations
E9(i,j), E10(j,jp), E11(jp,k), E12;

E9(i,j)..
(sum((m),RtoT(i,m,j))*distance_RtoT(i,j)*transcost)=e=Cost_RtoT(i,j);
E10(j,jp)..
(sum((m),TtoT(j,m,jp))*distance_TtoT(j,jp)*transcost)=e=Cost_TtoT(j,j
p);
E11(jp,k)..
(sum((m),TtoD(jp,m,k))*distance_TtoD(jp,k)*transcost)=e=Cost_TtoD(jp,
k);
E12..
(sum((i,j),Cost_RtoT(i,j)))+(sum((j,jp),Cost_TtoT(j,jp)))+(sum((jp,k)
,Cost_TtoD(jp,k)))=e=Ttranscost;

* TRANSPORTATION end


* Profit
Parameter
value(m) selling value /PS 120, OPF 110, EFB 105, PKT 65, PMF 75, SW
50, HW 85, BO 300, BE 450, SG 325, PW 260/;

Positive Variable
Z7(m),Z7b, Z8(m), Z9(m),Z9b, profit;

Variable
totalprofit;

Equation
E13(m),E13b, E15(m),E15b, E16, obj  ;

* Total resources used in R
E13(m).. sum((i,j),RtoT(i,m,j))=e=Z7(m);

* Total amount used in purchasing raw material
E13b.. sum((m),((Z7(m))*value(m)))=e=Z7b;
```

```
* Total product send to D
E15(m).. sum((jp,k),TtoD(jp,m,k))=e=Z9(m);

* Total sell in D
E15b.. sum((m),((Z9(m))*value(m)))=e=Z9b;

E16.. Z9b-Z7b=e=profit;
obj.. Totalprofit=e=profit-Ttranscost ;


Model MarkII /all/;

Solve MarkII using LP maximising Totalprofit;

display RtoT.l, TtoT.l, TtoD.l, Totalprofit.l;
```