Novel Sustainable Evaluation Approach for Multi-Biomass Supply Chain

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Abstract

After the oil crisis held in 1973 and 1979, academicians and industry players have noticed the importance and necessity of having alternative and sustainable energy sources in future. Biological wastes, also named as "Biomass" has been cited as one of the significant sustainable energy sources. Biomass poses an ideal and substantial potential to achieve a sustainable system. However, the development of biomass industry is still relatively sluggish due to the lack of confidence of the investor to venture in this relatively new green business. This is most probably attributed to the low-maturation of biomass technologies compared to other conventional technologies, high logistics cost required for biomass transportation and uncertain market penetration barrier for the biomass-derived products. This raises the importance of having a proper biomass management system and a systematic evaluation approach to assess the sustainability performances of the biomass industry.

Therefore, the ultimate goal of this thesis is to develop a sustainable multi-biomass supply chain with the aims of optimising all three sustainability dimensions simultaneously. A sustainable multi-biomass supply chain is referred as the integrated value chain of the green products, which derived from various types of biomass, starting from harvesting stage to the final products delivery stage. This thesis discusses in detail on the relevant previous research works toward the introduction of novel evaluation approach to attain different sustainable objectives (i.e., economic, environmental and social) simultaneously. The evaluation approach encompasses various components, including (i) model reduction by using P-graph integrated two-stage optimisation approach; (ii) consideration of vehicle capacity constraint for detailed transportation cost estimation; (iii) integration of various sustainability indexes using various optimisation techniques.

On top of that, two novel debottlenecking approaches, one through principal component analysis (PCA) method; while another through P-graph framework, which able to identify and remove barriers that limit the sustainability performance of the biomass supply chain, are proposed. Aside from this, this thesis also aims to reduce the gaps between the researchers and industry players by developing some user-friendly and non-programming-background dependent decision-making tools. Thus, decision-makers are able to understand the insight of their problems easily without requirement of strong mathematical background. A case study in Johor, a southern state in Malaysia, which is endowed with extensive biomass resources, is used to demonstrate the effective of the proposed approaches.

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List of Publications

Journal Publications

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Nomenclatures

Abbreviation	
ABB	Accelerated branch-and-bound
ACGIH	American conference of government industrial hygienists
ACO	Ant colony optimisation
AD	Anaerobic digestion
ADP	Abiotic depletion potential
AFEX	Ammonia fibre explosion
AHI	Atmospheric hazard index
AHP	Analytical hierarchy process
AP	Acidification/ acid-rain potential
ATP	Aquatic toxicity potential
BA	Bees algorithm
BCR	Benefit-cost ratio
BSCM	Biomass supply chain management
CAPEX	Capital expenditure
CF	Carbon footprint
CFC	Chlorofluorocarbon
COD	Chemical oxygen demand
CSR	Corporate social responsibility
DLF	Dry long fibre
DOA	Department of agriculture
EF	Ecological footprint
EFB	Empty fruit branch
EHI	Environmental hazard index
ENF	Energy footprint

ESPM	Environmental performance strategy map
FEF	Food-to-energy footprint
FLFP	Female labour force participation
FT	Fischer-Tropsch
GA	Genetic algorithm
GDP	Gross domestic product
GHG	Greenhouse gases
GSCM	Green supply chain management
GWP	Global warming potential
HFC	Hydrofluorocarbon
HH	Health hazard index
HP	High potential
HPS	High pressure steam
HQI	Hazard quotient index
HTPE	Human toxicity potential by either inhalation or derma exposure
HTPI	Human toxicity potential by ingestion
ICPHI	Inherent chemical and process hazard index
IEI	Integrated Environmental index
IETH	Inherent environmental toxicity hazard
IR	Incremental ratio
IRR	Internal rate of return
ISI	Inherent safety index
LCA	Life cycle analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LF	Land footprint
LHW	Liquid hot water

LP	Low potential
LSR	Logistical social responsibility
MH	Material hazard index
MIP	Mixed integers programming
MILP	Mixed integers linear programming
MOO	Multi-objective optimisation
MP	Medium potential
MPOC	Malaysian palm oil council
MPOB	Malaysian palm oil board
MSG	Maximal structure generator
NP	Nutrification potential
NPV	Net present value
ODP	Ozone depletion potential
OEL	Occupational exposure limit
OHHI	Occupational health hazard index
OPEX	Operating expenditure
OSHA	Occupational safety and health administration
PC	Principal component
PCA	Principal component analysis
PEI	Potential environmental impact
PIIS	Prototype inherent safety index
PKS	Palm kernel shell
PNS	Process network synthesis
POCP	Photochemical ozone creation potential
POF	Poverty footprint
PP	Payback period
PRI	Process route index

PRHI	Process route healthiness index
PSI	Process stream index
PSR	Purchasing social responsibility
ROI	Return on investment
SCM	Supply chain management
SCN	Supply chain network
SME	Small and medium enterprise
SOO	Single-objective optimisation
SPI	Sustainable process index
SSCM	Sustainable supply chain management
SSG	Solution structure generator
SVS	Smart vehicle selection
TC	Threshold cut
TR	Threshold ratio
TTP	Terrestrial toxicity potential
VLM	Volume-limiting material
VOC	Volatile organic compound
VOL	Volume-limiting
WAO	Wet air oxidation
WAR	Waste reduction
WEC	Worker exposure concentration
WEL	Weight-limiting
WF	Water footprint
WLM	Weight-limiting material
WO	Wet oxidation
WPFP	Workplace Footprint

Indices	
a	index for pollutants
b	index for variable (sustainability indicator)
i	index for biomass sources
j	index for centralized hubs
k	index for customers
m, *m'*	index for transportation modes from source *i* to processing hub *j* and from processing hub *j* to customer *k*
n	index for process path
p	index for products
q	index for impact categories
r	index for biomass
s	index for responder
t, *t'*	index for technologies to produce intermediates *l* and products *p*
u	index for social impacts
z	index for principal components

Matrices	
$\boldsymbol{C}$	correlation matrix used in PCA
$\boldsymbol{E}$	eigenvector for PC
$\boldsymbol{I}$	identity matrix
$\boldsymbol{S}$	standardised original data matrix
$\boldsymbol{Y}$	projection matrix in PCA

Parameters	
$\mathrm{Area}^{\mathrm{Hub}}$	land area required for setting up a single processing hub [m^2/hub]
$\mathrm{Abs}^{\mathrm{CO_2}}$	CO_2 absorption rate by plantation [$tCO_2/(m^2.y)$]
$\mathrm{C}_r^{\mathrm{Biomass}}$	collection cost of biomass *r* [RM/t]

$C_t^{CAPEX\_Tech}$	annual capital cost of technology *t* [RM/t]
$C_{t'}^{CAPEX\_Tech}$	annual capital cost of technology *t'* [RM/t]
$C^{Construct}$	construction cost [RM]
C^{Fert}	fertilising cost required for plantation [RM/m^2]
C^{Fuel}	diesel price [RM/L]
C^{Fuel_Plantt}	fuel cost required for plantation [RM/m^2]
$C_r^{General}$	correlated cost constant [RM/t]
C^{Labour_Plantt}	labour cost required for plantation [RM/m^2]
C^{Land}	land cost [RM]
$C_t^{OPEX\_Tech}$	annual operating cost of technology *t* [RM/t]
$C_{t'}^{OPEX\_Tech}$	annual operating cost of technology *t'* [RM/t]
C^{Plantt}	plantation cost [RM/(m^2.y)]
C_m^{Proc}	purchasing cost of transportation mode *m* [RM]
$C_{m'}^{Proc}$	purchasing cost of transportation mode *m'* [RM]
C_p^{Prod}	revenue obtained from product *p* [RM/t]
C_m^{Repair}	repair cost of transportation mode *m* [RM/km]
$C_{m'}^{Repair}$	repair cost of transportation mode *m'* [RM/km]
C^T	linearised transportation cost constant [RM/t/km]
Cap_m^{Weight}	weight limit of transportation mode *m* [t/trip]
$Cap_{m'}^{Weight}$	weight limit of transportation mode *m'* [t/trip]
CRF	capital recovery factor
$d_{i,j}$	travelling distance from source *i* to processing hub *j* [km]
$d_{j,k}$	travelling distance from processing hub *j* to customer *k* [km]
DT_m	Delay time due to loading and unloading process for transportation mode *m* [h/trip]

$\mathrm{DT}_{m'}$	Delay time due to loading and unloading process for transportation mode *m'* [h/trip]
$\mathrm{EI}_q^{(\mathrm{L})}$	lower bound of the environmental impact at category *q* caused by the entire supply chain [t-eq/y]
$\mathrm{EI}_q^{(\mathrm{U})}$	upper bound of the environmental impact at category *q* caused by the entire supply chain [t-eq/y]
$\mathrm{F}_{r,i}$	amount of biomass *r* available in source *i* [t/d]
$\mathrm{frac}^{\mathrm{ab\_Ocean}}$	fraction of CO_2 absorbed by ocean [%]
frac_n	Fraction of material that processed in process *n* [%]
$\mathrm{fac}_{a,t}$	emission factor of pollutant *a* through technology *t* [t pollutant *a*/t intermediate *l*]
$\mathrm{fac}_{a,t'}$	emission factor of pollutant *a* through technology *t'* [t pollutant *a*/t biomass *r*]
$\mathrm{fac}_m^{\mathrm{CO_2}}$	carbon emission factor for transportation mode *m* [gCO_2/km]
$\mathrm{fac}_{m'}^{\mathrm{CO_2}}$	carbon emission factor for transportation mode *m'* [gCO_2/km]
HW	hourly wage [RM/h]
$\mathrm{LC}_{50\ a}$	lethal concentration which caused 50 % death of this fish
$\mathrm{LD}_{50\ a}$	lethal dose that caused 50 % death of rat
$\mathrm{LS}^{\mathrm{Hub}}$	life span of processing hub [y]
$\mathrm{LS}^{\mathrm{Plantt}}$	life span of the plantation [y]
$\mathrm{LS}_m^{\mathrm{Tr}}$	life span of the transportation mode *m* [y]
$\mathrm{LS}_{m'}^{\mathrm{Tr}}$	life span of the transportation mode *m'* [y]
M	maximum hub's capacity [t/d]
$\mathrm{num}_{i,m,j}^{\mathrm{Trip\_Max}}$	maximum number of trip for transportation mode *m* to deliver biomass from source *i* to processing hub *j* [trip/(vehicle.d)]
$\mathrm{num}_{j,m',k}^{\mathrm{Trip\_Max}}$	maximum number of trip for transportation mode *m'* to deliver biomass from processing hub *j* to customer *k* [trip/(vehicle.d)]
$\mathrm{OH}^{\mathrm{Max}}$	maximum operating hour [h/d]
$\mathrm{OH}_{i,m,j}$	time required to transport biomass from source *i* to processing hub *j* via transportation mode *m* [h]

$\mathrm{OH}_{j,m',k}$	time required to transport biomass from processing hub *j* to customer *k* via transportation mode *m'* [h]
OPD	estimated annual working days [d/y]
$\mathrm{P}_{m}{}^{\mathrm{Fatality}}$	risk of pedestrian fatality for transportation mode *m*
$\mathrm{rate}_{m}^{\mathrm{Fuel}}$	fuel consumption rate for transportation mode *m* [L/km]
$\mathrm{rate}_{m'}^{\mathrm{Fuel}}$	fuel consumption rate for transportation mode *m'* [L/km]
$\mathrm{rate}^{\mathrm{int}}$	discount rate [%]
RI	random consistency index
$\mathrm{Sp}_{m}^{\mathrm{Impact}}$	impact speed [km/h]
$\mathrm{Sp}_{m}^{\mathrm{Max}}$	maximum speed can be achieved by transportation mode *m* [km/h]
$\mathrm{Sp}_{m'}^{\mathrm{Max}}$	maximum speed can be achieved by transportation mode *m'* [km/h]
$\mathrm{Sp}_{m}^{\mathrm{Mean}}$	mean speed of transportation mode *m* [km/h]
$\mathrm{Sp}_{m'}^{\mathrm{Mean}}$	mean speed of transportation mode *m'* [km/h]
$\mathrm{Sp}_{m}^{\mathrm{Min}}$	minimum speed can be achieved by transportation mode *m* [km/h]
$\mathrm{Sp}_{m'}^{\mathrm{Min}}$	minimum speed can be achieved by transportation mode *m'* [km/h]
$\mathrm{TLV}^{\mathrm{TWA}}$	time-weighted averages of threshold limit values [ppm]
w^{Ec}	relative priority of the economic objective
w^{En}	relative priority of the environmental objective
w^{Sc}	relative priority of the social objective
w_{q}	relative importance of the environmental impact *q*
w_{u}	relative importance of the social impact *u*
$\mathrm{X}_{l,t',p}$	conversion ratio of intermediate *l* to product *p* via technology *t'*
$\mathrm{X}_{r,t,l}$	conversion ratio of biomass *r* to intermediate *p* via technology *t*
$\mathrm{X}_{r,t}^{\mathrm{Elec}}$	energy conversion factor for technology *t* [MJ/t]
$\mathrm{X}_{l,t'}^{\mathrm{Elec}}$	energy conversion factor for technology *t'* [MJ/t]
$\mathrm{Y}_{t}^{\mathrm{Elec}}$	energy requirement for technology *t* [MJ/t]

$Y_{t'}^{\text{Elec}}$	energy requirement for technology *t'* [MJ/t]
Y_{t}^{Water}	water requirement for technology *t* [m^3/t]
$Y_{t'}^{\text{Water}}$	water requirement for technology *t'* [m^3/t]
α_v	maximum volume of VLM that can be delivered by one vehicle [m^3/d]
α_w	maximum weight of WLM that can be delivered by one vehicle [t/d]
$\Psi_{a,q}$	score of potential environmental impact of pollutant *a* at category *q* [t-eq/t]
$\Psi_{p,q}$	score of potential environmental impact of product *p* at category *q* [t-eq/t]
Ψ_{q}^{Fossil}	score of potential environmental impact of fossil-based energy at category *q* [t-eq/t]
$\Psi_{u=HTPE}$	score of social impact in terms of human toxicity potential by inhalation and dermal exposure [ppm^{-1}]
$\Psi_{u=HTPI}$	score of social impact in terms of human toxicity potential by ingestion [kg/mg]

Variables

B_j	binary variables to denote the selection of processing hub *j*
$C^{\text{CAPEX\_Tr}}$	capital expenditure for transportation system [RM/y]
C^{GP}	annual gross profit [RM/y]
C^{Inv}	investment cost (hub and transportation cost) [RM/y]
$C^{\text{Inv\_Hub}}$	annualised hub investment cost [RM/y]
C^{Labour}	labour cost for transportation system [RM/d]
C^{Maintc}	maintenance cost for transportation system [RM/y]
C^{Mileage}	mileage cost [RM/d]
C^{NP}	annual net profit [RM/y]
$C^{\text{OPEX\_Tr}}$	operating expenditure for transportation system [RM/y]
$C^{\text{Penalty\_CO}_2}$	carbon emission penalty [RM/y]

C^{Tr}	annual transportation cost [RM/y]
CI	consistency index
CF^{Total}	total carbon footprint [m^2/(t/y)]
CR	consistency ratio
EI_q	environmental impact at category q [t-eq/y]
EI_q^{Elec}	environmental impact at category q due to energy consumption [t-eq/y]
EI_q^{GenE}	environmental impact at category q due to self-generated energy [t-eq/y]
$EI_q^{\mathrm{GenE\_Direct}}$	direct environmental impact at category q due to self-generated energy [t-eq/y]
$EI_q^{\mathrm{GenE\_Indirect}}$	indirect environmental impact at category q due to self-generated energy [t-eq/y]
EI_q^{ImpE}	environmental impact at category q due to imported energy [t-eq/y]
EI_q^{Process}	environmental impact at category q due to pollutant emission during conversion process [t-eq/y]
EI_q^{Prod}	environmental impact at category q due to manufactured product [t-eq/y]
$EI_q^{\mathrm{Prod\_Direct}}$	direct environmental impact at category q due to manufactured product [t-eq/y]
$EI_q^{\mathrm{Prod\_Indirect}}$	indirect environmental impact at category q due to manufactured product [t-eq/y]
EI_q^{Tr}	environmental impact at category q due to fuel consumption during transportation [t-eq/y]
$Elec^{\mathrm{Exp}}$	total electricity exported [MJ/y]
$Elec^{\mathrm{Gen}}$	total electricity generated [MJ/y]
$Elec^{\mathrm{Imp}}$	total electricity imported [MJ/y]
$Elec^{\mathrm{Req}}$	total electricity required [MJ/y]
F^{Fuel}	total annual fuel consumed for the transportation [L/y]

$F^{\text{FossilFuel\_Sub}}$	amount of fossil-based fuel being substituted by the biofuel or bioenergy generated [t/y]
F_a	total emission rate of pollutant *a* [t/y]
$F_{l,j}$	flowrate of intermediate *l* produced in hub *j* [t/d]
$F_{l,t',j}$	flowrate of intermediate *l* in hub *j* which sent to technology *t'* [t/d]
$F_{p,j}$	flowrate of product *p* produced in hub *j* [t/d]
$F_{p,,j,k}$	flowrate of product *p* from hub *j* to customer *k* [t/d]
$F_{p,j,m',k}$	flowrate of product *p* from processing hub *j* to customer *k* via transportation mode *m'* [t/y]
$F_{p,j,m',k}^{\text{Volume}}$	volumetric flowrate of product *p* from processing hub *j* to customer *k* via a single transportation mode *m'* [m^3/y]
$F_{p,j,m',k}^{\text{Weight}}$	mass flowrate of product *p* from processing hub *j* to customer *k* via a single transportation mode *m'* [t/y]
$F_{r,i,j}$	flowrate of biomass *r* from source *i* to hub *j* [t/d]
$F_{r,i,m,j}$	flowrate of biomass *r* from source *i* to processing hub *j* via transportation mode *m* [t/y]
$F_{r,i,m,j}^{\text{Volume}}$	volumetric flowrate of biomass *r* from source *i* to processing hub *j* via a single transportation mode *m* [m^3/d]
$F_{r,i,m,j}^{\text{Weight}}$	mass flowrate of biomass *r* from source *i* to processing hub *j* via a single transportation mode *m* [t/d]
$F_{r,j}$	flowrate of biomass *r* delivered to hub *j* [t/d]
$F_{r,t,j}$	flowrate of biomass *r* in hub *j* which sent to technology *t* [t/d]
I_n^{CI}	inherent safety in terms of chemical factors for process *n*
$I_n^{\text{COR,Max}}$	inherent safety in terms of chemical corrosiveness for process *n*
$I_n^{\text{ES,Max}}$	inherent safety in terms of equipment safety for process *n*
I_n^{EX}	inherent safety in terms of explosiveness for process *n*
I_n^{FL}	inherent safety in terms of flammability for process *n*
$I_n^{\text{INT,Max}}$	inherent safety in terms of chemical interaction for process *n*
I_n^{Inv}	inherent safety in terms of process inventory for process *n*

I_n^{PI}	inherent safety of the process for process *n*
I_n^{Press}	inherent safety in terms of process pressure for process *n*
$\mathrm{I}_n^{\mathrm{RM,Max}}$	inherent safety in terms of heat of main reaction for process *n*
$I_n^{\mathrm{RS,Max}}$	inherent safety in terms of heat of side reaction for process *n*
$I_n^{\mathrm{ST,Max}}$	inherent safety in terms of safe process structure for process *n*
I_n^{Temp}	inherent safety in terms of process temperature for process *n*
I_n^{TI}	total inherent safety index for process *n*
I_n^{TOX}	inherent safety in terms of toxic exposure for process *n*
ISI	inherent safety index
JC	job vacancies created by the biomass supply chain [job]
JC_n^{Direct}	direct job created by process *n* [job]
JC_n^{Indirect}	indirect job created by process *n* [job]
LF^{Total}	total land footprint [m^2]
Mag	polar magnitude for the *s*-vector
Mag_n	polar magnitude for the *s*-vector of process *n*
$MATD_r$	maximum allowable travel distance [km]
num^{Hub}	number of hubs
$num_{i,m,j}^{\mathrm{Trip}}$	number of trip required to transport material from source *i* to processing hub *j* via transportation mode *m* [trip/d]
$num_{j,m',k}^{\mathrm{Trip}}$	number of trip required to transport material from processing hub *j* to customer *k* via transportation mode *m'* [trip/d]
num^{Vehicle}	number of vehicle required
$num_{i,m,j}^{\mathrm{Vehicle}}$	number of transportation mode *m* required to deliver biomass from source *i* to processing hub *j*
$num_{j,m',k}^{\mathrm{Vehicle}}$	number of transportation mode *m'* required to deliver product from processing hub *j* to customer *k*
$Perf^{\mathrm{After}}$	performance of before debottlenecking
$Perf^{\mathrm{Before}}$	performance of after debottlenecking

$Perf^{\mathrm{Op}}$	performance of optimal solution
$Perf^{\mathrm{Sub}}$	performance of sub-optimal solution
SI_u	social impact in terms of human toxicity potential
SI_u^{Process}	social impact in terms of human toxicity potential due to the pollutant emitted from the conversion process
SI_u^{Prod}	social impact in terms of human toxicity potential due to the product
SI_u^{Elec}	social impact in terms of human toxicity potential due to the energy consumption in the hub
SI_u^{Tr}	social impact in terms of human toxicity potential due to the fuel consumption during transportation
TCE^{Tr}	total carbon emission resulted from transportation [tCO_2/y]
VAR_z	total variance described by z^{th} PC
WF^{Total}	total water footprint [m^3/y]
$x^{\mathrm{standardised}}$	standardised value of data
θ	polar angle for the *s*-vector
θ_n	polar angle for the *s*-vector of process *n*
λ	degree of satisfaction of the objective
λ^{Max}	maximum eigenvalue used in AHP
λ^{Ec}	degree of satisfaction based on economic performance in SCM
λ^{En}	degree of satisfaction based on environmental performance in SCM
λ^{Least}	degree of satisfaction for the least satisfied objective
λ^{PC}	eigenvalue determined in PCA
λ^{PC_z}	degree of satisfaction for the z^{th} PC
λ^{Sc}	degree of satisfaction based on social performance in SCM
λ_u^{Sc}	degree of satisfaction of each social impact *u*
λ^{SCM}	overall degree of satisfaction of the SCM

Chapter 1:

Introduction

1.1 Background

Sustainability development and cleaner production have progressively become the main concern in the world. This is mainly driven by the snowballing global pressure on emission reduction and the increasing social awareness among communities. In the Malaysian context, biomass utilisation has been cited as one of the prospective solutions to achieve sustainable (Duić et al., 2011). However, the development of biomass industry is still relatively sluggish due to various inveterate barriers (e.g., high logistic cost due to low-density biomass transportation; and low level of involvement of investor due to market uncertainty) (MIGHT, 2013). This raises the importance of having a proper biomass management system and a systematic evaluation approach to assess the sustainability performances of the biomass industry. Therefore, it is suggested to develop a multi-biomass supply chain, which fully utilise the potential of biomass, including palm oil biomass (empty fruit brunch and palm kernel shell), paddy biomass (rice husk and paddy straw), pineapple peel and sugarcane bagasse, in order to promote the sustainability development of renewable energy in Malaysia (Lam et al., 2013). Despite numerous studies were conducted in biomass supply chain optimisation, most of them did not consider the social sustainability in their optimisation model. Thus, this research also contributes a novel evaluation approach, which able to synthesise a sustainable biomass supply chain with the aim of optimising all three sustainability dimensions (economic, environmental and social) simultaneously. Aside from this, the development of debottlenecking approach to detect the underlying bottlenecks that hamper the development of biomass industry in Malaysia is another key contribution of this work.

1.2 Problem Statement

Biomass has been idnetified as one of the prospective alternative resources for process industry to achieve sustainability. However, development of biomass industry in Malaysia is still kept at pioneered stage. The main issues to be addressed are:

I. Some of the underutilised biomass (i.e., yet to have well established technology), which contain substantial economic potential are not considered in most works.

II. Most works merely focus on economic and environmental sustainability, social sustainability receives least attention during the optimisation process.

III. Lack of systematic debottlenecking approach that able to detect barriers that restrict the sustainability performance of the biomass supply chain.

Therefore, several novel approaches which capable to measure sustainability performance, including economic, environmental and social dimension (mainly referring to health and safety aspects) of the multi-biomass supply chain; optimise the multi-biomass supply chain based on the sustainability performance; and detect bottlenecks of biomass industry and subsequently remove them.

1.3 Research Objective

The main objective of this research work is to develop a sustainable biomass supply chain from the chemical engineering point of view. It can be further broken down into several goals:

1.3.1 To synthesise a multi-biomass supply chain which integrates the available biomass

To-date, some of the valuable biomass in Malaysia have yet to receive sufficient attention in both research and industrial application (e.g., sugarcane bagasse, pineapple peel, etc.). Therefore, a multi-biomass supply chain, which considers a broader range of processes for various types of biomass (obtained from different agriculture sources) in a single supply chain should be synthesised. Contrarily, single-biomass supply chain only considers the processes for a single type of biomass in the supply chain. Hence, the opportunity of having integration between supply chains is higher for multi-biomass supply chain compared to the conventional single-biomass supply chain. For instance, electricity generated from combustion of one biomass can be consumed by the process facility used for another biomass. The enhancement of integration will gradually improve the energy efficiency and resource conservation in the biomass industry.

1.3.2 To evaluate the sustainability performances of the integrated biomass supply chain

Without a proper and systematic approach, the future development of biomass supply chain management (BSCM) can never move forward. In fact, this is vital for the potential investors in their robust assessments of the biomass industry. Therefore, novel evaluation approach which integrates all three sustainability dimensions (i.e., economic, environmental, social) of the supply chain model is developed.

1.3.3 To develop a systematic bottleneck targeting approach to identify the bottlenecks occur in the supply chain network

Bottlenecks in supply chain refer to the barriers that limit a given design or process in attaining a higher performance (e.g., limited availability of biomass which lead to low economic feasibility of the business, low-volume density of biomass which lead to high transportation cost, etc.). To-date, the conventional bottleneck detection methods are merely invented to identify physical barriers that limit the throughput or makespan of the process. However, in order to promote sustainable development, the concept of bottlenecks should be extended to cover the other two sustainability dimensions (i.e., environmental and social). For instance, high environmental impact and high safety risk can be the barriers which cause unfavourability of a given system. Thus, there is a need to develop a systematic debottlenecking approach which able to identify these bottlenecks and subsequently remove them.

1.4 Research Contributions

The research is proposed to be carried out mainly with the aid of two optimisation software, i.e., Lingo v14.0 with global solver (Lingo, 2015) and P-graph Studio v5.2.0.7 (P-Graph Studio, 2017). The summary of the research contribution of this thesis is listed as follow:

1.4.1 Development of comprehensive methodology to synthesise a multi-biomass supply chain which integrates several types of biomass available in Malaysia

The multi-biomass supply chain problem is a high complexity-huge size problem which required longer computing time. Therefore, a P-graph aided approach is developed to synthesise a biomass supply chain in Malaysia. A case study in Johor

State, Peninsular Malaysia is used to demonstrate the proposed method. Note that this biomass supply chain network is served as the base case in this research.

1.4.2 Development of a transportation decision tool with consideration of vehicle capacity constraints

In order to increase the reliability of the base case model, the capacity constraint of the transportation modes (i.e., weight and volume) are taken into consideration. In order to address this problem, a novel mathematical model is developed. Aside from this, a graphical tool called "Smart Vehicle Selection (SVS) Diagram" has been developed to increase the efficiency of the decision-making process.

1.4.3 Development of an evaluation model to evaluate and optimise the environmental sustainability of the integrated biomass supply chain

An evaluation model which encompasses several categories of environmental impacts is developed in order to determine a compromise solution for economic-environmental decision in supply chain management (SCM). On top of that, a graphical illustration method is proposed to show the tendency of a process toward each sustainability dimension.

1.4.4 Development of a mathematical model to evaluate and optimise the social sustainability of the integrated biomass supply chain

The model is extended to integrate social indicators (mainly focusing on safety aspect, health aspect and job creation) into the evaluation model. As a result, the sustainability performance of the SCM in terms of economic, environmental and social dimensions are measured and improved. However, the consideration of numerous sustainability indicators in a single model might cause redundancy in data set. This will make the results become hard to be analysed and diagnosed. Therefore, a novel PCA-aided optimisation approach is introduced.

1.4.5 Debottlenecking of integrated biomass supply chain which limits its sustainability performance

Apart from setting a throughput capacity for supply chain, the bottleneck also limits the sustainability performance of the supply chain in terms of economic, environmental and social dimensions. Thus, a systematic debottlenecking approach which able to improve the sustainability performance of the integrated biomass supply chain is developed in this work.

1.5 Outline of Thesis

This thesis is organised as follows: Chapter 2 presents a detailed literature review for this research (e.g., biomass potential, biomass availability in Malaysia, potential technologies, available optimisation and evaluation approaches, etc.), while Chapter 3 outlines the research strategies and methods opted in this work. In Chapter 4, a novel P-graph aided two-stage optimisation model is proposed to solve the multi-biomass supply chain problem. The model is then improved by consideration of vehicle capacity constraints in Chapter 5, in order to deliver a more accurate estimation on transportation cost. Chapter 6 focuses on integrating several environmental indicators into the evaluation model, while Chapter 7 aims to extend the model to cover the social impacts of the biomass supply chain. It is then followed by the development of debottlenecking framework for biomass supply chain in Chapter 8, while concluding remarks are given in Chapter 9.

Chapter 2:

Literature Review

2.1 Introduction

In Malaysia, agriculture industries make up twelve percent of the nation's Gross Domestic Product (GDP) (DOSM, 2015). The huge amount of biomass is the side products produced from the rapid development in agriculture industries. As reported, a minimum of 168 million tonnes of biomass is generated annually, where palm oil biomass accounts for 94 % of biomass feedstocks, wood biomass contributes 4 %, and the remaining contributors are agricultural by-products (i.e., sugarcane, pineapple, paddy, etc.) (Nurhidayati & Leon, 2012). Yet, most of the biomass are not well utilised. This chapter presents the literature reviews related to this research and is organised as follow. Section 2.2 summarises the existing biomass in Malaysia. Section 2.3 outlines the available technologies for biomass conversion. The literature review related to supply chain management is presented in Section 2.4. In Section 2.5, optimisation techniques which are commonly used are introduced. It is followed by the reviews of conventional bottleneck detection methods in Section 2.6.

2.2 Biomass availability and economic potential

Malaysia is the world second largest producer of palm oil around the world. It contributed 39 % of the world production and 44 % of world oil export (MPOC, 2014). With such amount of palm oil production, the amount of palm oil biomass is also tremendous. It is estimated that for each kg of palm oil generated, approximately 4 kg of palm oil biomass (i.e., empty fruit brunch (EFB), palm kernel shell (PKS), fronds, trunks, etc.) is produced (Abdullah & Sulaiman, 2013). Traditionally, palm oil biomass (especially empty fruit bunches) is commonly used as fuel stock in palm oil plant operations. Apart from that, the palm oil biomass be converted by digestion (enzymatic, concentrated or diluted acid hydrolysis) as fermentation feedstock to produce several value-added products, i.e., ethanol (Sudiyani et al., 2013), bio-gas (Srimachai et al., 2014), acetone (Al-Shorgani et al., 2012) and energy pack (Ng et al., 2014).

Besides, paddy is another important crop in Malaysia as rice is a crucial part of every Malaysian diet. According to Department of Agriculture Malaysia, paddy planted area throughout Malaysia is estimated as 674,332 hectares while the average paddy yield is around 3.879 metric tonnes per hectare (DOA, 2014). The cultivation of rice results in two types of biomass, i.e., paddy straw and rice husk. Both have attractive potential in terms of energy due to their high energy content, i.e., 15.09 MJ/kg and 15.84 MJ/kg respectively (Lim et al., 2012). Besides, the silica ashes derived from the rice husk (Kartini, 2011) and paddy straw (Munshi et al., 2013) can be used as renewable pozzolanic additive in cement paste. However, there is still limited commercial building systems have been developed using these materials on large-scales. Instead of using these paddy biomass as building materials, it is more common to be used in mineral mix for composting (Theeba et al., 2012).

In addition, sugarcane is another important agriculture crops in Malaysia. The production of sugar from sugarcane yields vast amount of biomass in the form of molasses, vinasse and bagasse. In the past decades, the lignocelluloses biomass such as bagasse are converted into furfural as a renewable substitute for synthetic resins (Uppal et al., 2008). Recently, sugarcane waste can be used in different areas. For instance, the sugarcane wastes can be converted into second generation ethanol (Cardona et al., 2010), paper paste (Pattra et al., 2008) and energy (Ramjeawon, 2008).

Furthermore, pineapple waste (i.e., pineapple peel from pineapple juice factories) is another potential biomass that can be converted into value-added product. Occasionally, the wastes are utilised as fertiliser or animal feed (Lim & Matu, 2015). Although some researchers have reported that pineapple waste is not suitable to be processed as animal feed due to its high fibre and soluble carbohydrate content with low protein content (Correia et al., 2004), but the recent research results proved that dehydrated pineapple by-products will increase the digestibility of animals which eventually lead to an increment in the animals' weight (Costa et al., 2007). Besides, the pineapple peel which consist of cellulose, hemicelluloses and carbohydrate is suitable to be produced into paper, cloth, etc. (Hepton & Hodgson, 2003). Recently, many researchers have raised their interest in converting these pineapple wastes into methane (Rani & Nand, 2004), ethanol (Choonut et al., 2014), citric acid (Chau & David, 1995) and formic acid (Zakaria & Nazeri, 2012).

Despite the economic potential of these biomass were widely discussed by the academicians, but there are very few works are conducted to integrate these of biomass into the supply chain. Table 2.1 summaries the overall plantation area of each agriculture crop in Malaysia.

Table 2.1： Hectarage of plantation area of each crop in Malaysia according to states.

State	Plantation Area (ha)			
	Oil Palm	Pineapple	Sugar Cane	Paddy
Johor	201,018.0	8,691.8	80.7	3,022.1
Kedah	21,091.2	760.5	25.5	215,930.0
Kelantan	3,210.5	307.2	22.0	70,939.1
Melacca	9,379.0	-	11.0	2,228.6
N. Sembilan	19,334.1	102.1	0.2	2,016.4
Pahang	36,350.1	281.4	30.6	8,351.4
Perak	98,280.8	43.7	1.0	82,150.2
Perlis	58.2	1.0	4,098.9	52,075.0
P. Penang	8,486.4	680.4	0.2	25,564.0
Selangor	38,543.4	523.4	-	37,460.1
Terengganu	1,895.0	86.2	26.6	17,851.5
Sabah	24,852.2	1,308.2	49.0	43,331.2
Sarawak	11,982.1	2,136.2	-	127,023.1
Sources	(MPOB, 2012)	(DOA, 2012)	(DOA, 2013)	(DOA, 2014)

2.3 Biomass Conversion

To-date, there are many different ways of converting biomass to value-added products and energy, including various biological, chemical and thermal processes. Figure 2.1 shows the conventional biomass utilisation paths. Note that, the conversion can be either result in final product (reached commercial levels of supply and demand) or may be a pre-processing stage for further processes.

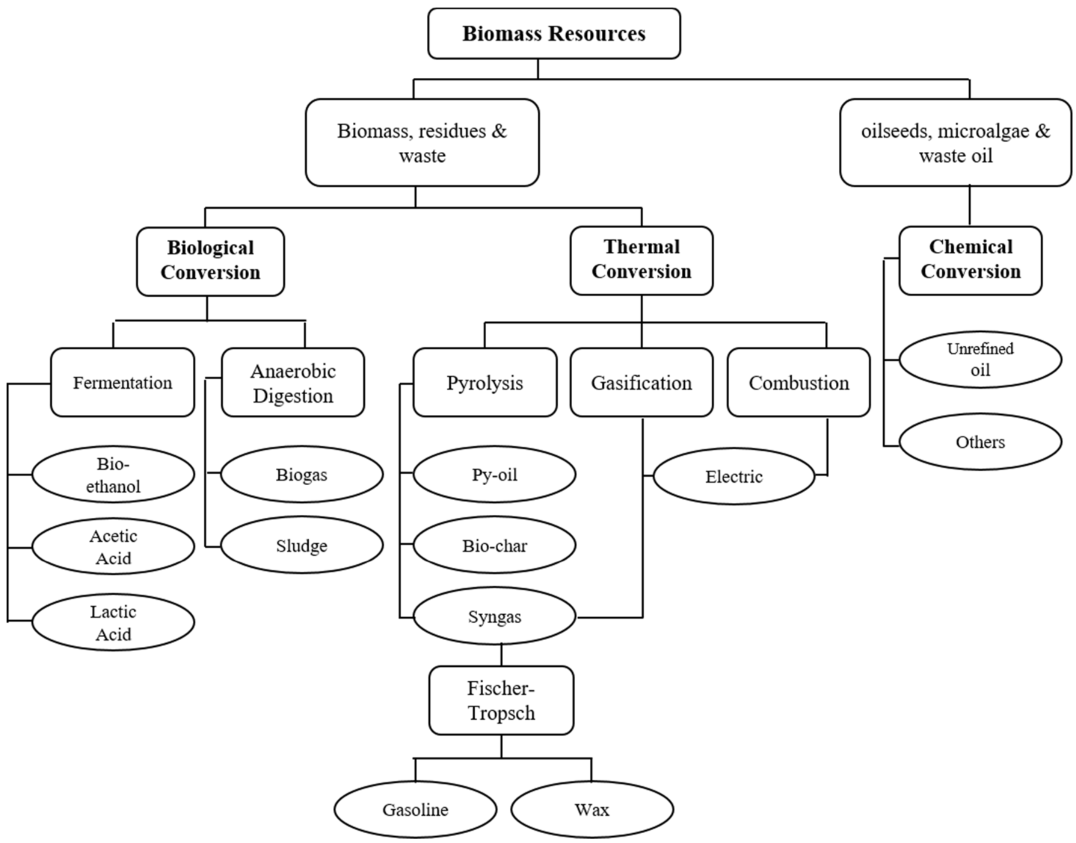

Figure 2.1: Conversion options for biomass (Williams, 2010).

2.3.1 Biological conversion

Biological conversion is one of the well-developed technologies used for the biomass conversion. It consists of two main routes, i.e., fermentation and anaerobic digestion.

2.3.1.1 Fermentation

Agriculture crops (e.g., sugarcane) which consist of high sugar content are the main feedstock for the fermentation process in order to covert the sugars into bio-ethanol. On the other hand, lignocellulosic source can also be used as feedstock for fermentation (Sun & Cheng, 2002). In the past decades, several types of biomass have been tested to produce bio-ethanol, such as sugarcane bagasse (Azzam, 1989), pineapple peels (Ruangviriyachai et al., 2010), rice husks (Fujieda et al., 2012), rice straws (Sasaki et al., 2013), empty palm fruit bunches (Kim & Kim, 2013), corn straw (Wang et al., 2015), etc.

The conversion includes two processes, i.e., (i) hydrolysis of cellulose in the lignocellulosic sources to fermentable reducing sugars and (ii) fermentation of the sugars to ethanol. Hydrolysis is usually catalysed by cellulose enzymes while fermentation is carried out by bacteria or yeast. Previous research has proved that the cellulose crystallinity, low porosity of the feedstock material and the presence of lignin and hemicellulose will reduce the efficiency of hydrolysis (McMillan, 1994). In order to address this issue, various pre-treatment processes were suggested by the researchers. The pre-treatment processes are aimed to: (i) improve the formation of sugars; (ii) prevent the degradation of carbohydrate; and (iii) prevent formation of by-products which inhibits the hydrolysis and fermentation processes (Sun & Cheng, 2002).

2.3.1.2 Anaerobic Digestion

Anaerobic digestion (AD) is an environmentally sustainable technology to manage organic waste, e.g., food waste, agriculture waste, industrial waste, etc. AD is a complex biological process in which the facultative and anaerobic microorganisms digest the organic material in the absence of oxygen in the order to obtain energy and simultaneously, released methane (CH_4) gas (Speece, 1983). AD involves four steps, i.e., hydrolysis, acidogenesis, acetogenesis and methanogenesis. During the hydrolysis, the enzymes excreted by fermentative bacteria decompose the complex and insoluble organic compounds (i.e., protein, carbohydrates and fats) into simple soluble compounds, e.g., fatty acids, amino acids, sugars and alcohols. During acidogenesis, these soluble compounds are converted into ethanol, propionate, butyrate, etc. In the acetogenesis phase, the long chain fatty acids are converted into acetate, hydrogen gas (H_2), CO_2, etc. Finally, during methanogenesis, methane-producing bacteria will convert the acetic acid into CH_4 gas (Shieh et al., 2000). It is worth to note that CH_4 gas can be used to generate electricity via gas-engine (Muench, 2015).

Similar to the fermentation, pre-treatment process is required prior to the AD. The objective of having pre-treatment is to expose the hemicellulose and cellulose to the microorganisms for the biodegradation process (Liu et al., 2009). In the recent decades, a number of studies have been conducted to determine the biogas yield of various biomass feedstock, including pineapple peels (Namsree et al., 2012), empty palm fruit bunches (Nieves et al., 2011), oil palm mesocarp fibre (Saidu et al., 2014), rice straws (Chen et al., 2015), rice husks (Jabeen et al., 2015), etc.

2.3.1.3 Pre-treatment Process

Generally, the pre-treatment processes are classified as physical pre-treatment, physio-chemical pre-treatment, chemical pre-treatment and biological pre-treatment. Physical treatment mainly aimed to increase the accessible areas and to reduce the cellulose crystallinity by reducing the size of the materials (10-30 mm after chipping and 0.2-2 mm after milling) (Cadoche & Lopez, 1989). As a result, the digestibility of the biomass is significantly improved (Millet et al., 1976). Besides, pyrolysis is another physical pre-treatment which able to improve the conversion rate of cellulose up to 80-85 % (Fan et al., 1987). Several types of physio-chemical pre-treatments are described as follow:

- **Steam explosion:** It is a hydrothermal pre-treatment process which the biomass is treated with high-pressure saturated steam (0.69-4.83 MPa; 160-260 ^{o}C) (McMillan, 1994). The pressure will then promptly reduce to atmospheric pressure in order to undergo an explosive decompression. This will cause the hemicellulose degradation and lignin transformation, thus increasing the rate of hydrolysis (Grous et al., 1986). Steam explosion has a lower energy requirement (70 % less) compared to the physical pre-treatment (Holtzapple et al., 1992). However, in order to remove the hydrolysis inhibitors generated through the pre-treatment process, the pre-treated biomass have to be washed by water (Mackie et al., 1985). Inevitably, 20-25 % of the reducing sugars generated by hydrolysis will also be removed along with the removed degradation products via the water (Mes-Hartree et al., 1988).

- **Liquid hot water (LHW):** LHW is another hydrothermal pre-treatment process which hydrolyses hemicellulose at elevated temperature and pressure. The superheated liquid water will be auto-ionised into hydronium ions, which act as a promoter for cleavage of ester bonds in the lignocellulosic materials, resulting in the formation of acetic acid (Teo et al., 2010). As a result, the cellulosic digestibility of the biomass is improved.

- **Ammonia fibre explosion (AFEX)**: Under AFEX pre-treatment, the biomass is treated with high-pressure liquid ammonia under a temperature ranging from 90 ^{o}C to 100 ^{o}C for 5 min and then the pressure is promptly reduced. Similar to steam explosion, this will cause a rapid decompression. As a result, the saccharification rate of the biomass has significantly improved (Teymouri et al., 2005). However, McMillan (1994) claimed that this pre-treatment is less effective for woody biomass.

The common chemical pre-treatment includes acid hydrolysis, alkaline hydrolysis, alkaline-peroxide hydrolysis and wet-oxidation:

- **Acid pre-treatment**: Lignocellulosic materials are treated with acids. Initially, concentrated acids have been widely used in the past decades to improve the hydrolysis rate. However, due to the high corrosiveness and hazardous of the concentrated acids, concentrated acid hydrolysis is less likely to be implemented (Silvers & Zacchi, 1995). Instead, dilute acid hydrolysis (e.g., dilute sulphuric acid (Chen et al., 2011), dilute phosphorus acid (Nieves et al., 2011), dilute hydrochloric acid (Herrera et al., 2004), etc.) has been proposed by the researchers. Literature has proven that the amount of hemicellulose in the dilute acid pre-treated biomass are much lower, resulting in higher yield of bio-ethanol ((Esteghlalian et al., 1997). Despite acid pre-treatment will improve the hydrolysis rate significantly, higher operating cost is required due to the need of neutralisation process to ensure the efficiency of downstream processes.

- **Alkaline pre-treatment**: Some bases (mostly dilute sodium hydroxide (NaOH)) can also be used for pre-treatment of lignocellulosic materials. The mechanism of this alkaline hydrolysis is believed to be saponification of the intermolecular ester bonds crosslinking xylan hemicelluloses. This will further lead to higher porosity of the lignocellulosic materials. In the recent studies, alkaline pre-treatment has shown its effectiveness in increasing the sugar yield for various biomass feedstock, such as rice straw (He et al., 2008), corn stover (Zheng et al., 2009), switch grass (Sills & Gossett, 2011), sugarcane bagasse (Rabelo et al., 2014), etc.

- **Wet oxidation (WO)**: WO is the process of treating the lignocellulosic materials with water and oxygen at 120 ^{o}C. It is also referred as referred as wet air oxidation (WAO) if air is used instead. WO process can be divided into two steps: (i) low temperature hydrolytic reaction and (ii) high temperature oxidative reaction (McGinnis et al., 1983).

In biological pre-treatment process, microorganisms, e.g., brown-, white- and soft-rot fungi are used to degrade lignin and hemicellulose in the ligocellulosic materials (Schurz, 1978). Generally, brown rots will destroy the cellulose, while white and soft rots will destroy both cellulose and lignin. Biological pre-treatment offers several advantages, e.g., lower capital cost, lower energy requirement, environmental friendly and required only mild environmental condition (Wang et al., 2013). The main drawbacks of biological pre-treatment are (i) long residence time per cycle of treatment process; (ii) requirement of sterile condition; and (iii) less effective compared to other pre-treatment processes (present lower yield in most of the cases) are still the major drawbacks of this technology (Menon & Rao, 2012).

2.3.2 Thermal conversion

Thermal conversion of the biomass basically covers three types of technologies, i.e., pyrolysis, gasification and combustion.

2.3.2.1 Pyrolysis

Pyrolysis is a thermochemical decomposition of dry organic materials (moisture content below 10 % mass fraction) in the absence of oxygen at moderate temperatures (350–550 °C) and atmospheric pressure. The product of pyrolysis encompasses of two forms, i.e., solids and volatiles.

The solid, also termed as bio-char, is a porous, high-carbon content biomass, which is widely used in soil management and water treatment (Inyang & Dickenson, 2015). Numerous studies have found that bio-char is able to reduce the organic contaminant bioavailability in soils with added benefits of improving the soil fertility (Zhang et al., 2010). Aside from this, it can be used as the catalyse for Fischer-Tropsch process (Dehkhoda et al., 2010) and adsorbent for organic contaminants and heavy metals presence in water (Inyang et al., 2014).

The volatiles can be partly condensed to give a liquid fraction (i.e., pyrolysis oil or py-oil) leaving a mixture of non-condensable gases, so-called syngas. Recent research shows that py-oil can be upgraded and served as an alternative transportation fuel (Elliott, 2013). Unlike the conventional coal- and petroleum-derived fuels, biomass oils contain less aromatics and sulphur, which will lead to severe environmental impact (Koçkar et al., 2000). Syngas is composed of carbon dioxide, carbon monoxide, methane, hydrogen and two carbon hydrogens. It could be processed into gasoline trough Fischer-Tropsch process (Mai et al., 2015). There are mainly two classes of pyrolysis processes, i.e., Fast Pyrolysis and Slow Pyrolysis:

- **Fast pyrolysis:** It is characterised by high heating rate (>10 K/s) and short vapour residence time. Feedstock used for this pyrolysis should be pre-treated to reduce the particle size (Wampler, 1995). The operating temperature is generally set above 500 ^{o}C. This will favour the formation of py-oil.

- **Slow pyrolysis**: It is characterised by slower heating rate (<1 K/s) and longer solid and liquid residence time (Wampler, 1995). It is usually operated at a lower temperature (roughly 400 ^{o}C) compared to fast pyrolysis. It is worth to note that under such condition, the yield of char is maximised (Bridgwater, 1999).

2.3.2.2 Gasification

Gasification is an alternative thermochemical conversion technology, which commonly used to treat biomass. The biomass is combusted inside a gasifier which filled with a controlled level of oxygen at a relatively high temperature (500-800 ^{o}C) (Lehmann & Joseph, 2009). Eventually, syngas and bio-char are generated. Numerous studies have been carried out to examine the syngas yield of various types of biomass feedstock. For instance, Mohammed et al. (2011) has investigated the gasification if empty fruit bunch in a fluidised bed reactor; Ahmed and Gupta (2012) examine the gasification of sugarcane bagasse under different temperature; Moghadam et al. (2014) has determined the optimum condition of syngas production from palm kernel shell.

2.3.2.3 Fischer-Tropsh

Fischer-Tropsch (FT) process provides an alternative route to produce clean fuels which contain of high cetane number (>70) from biomass, natural gas or coal (Torregrosa et al., 2013). The syngas generated from pyrolysis and gasification can be converted to valuable fuel or chemicals via FT process. Currently, there are two operating modes used for FT process, i.e., high temperature (300-350 ^{o}C) with iron-based catalyst FT process and low temperature (200-240 ^{o}C) with cobalt-based catalyst FT process. Generally, the former FT process is used for gasoline production while the latter FT process is used for waxes production (Dry, 2002).

2.3.2.4 Combustion

Biomass combustion is simply referred to the burning of biomass in a combustion furnace. To-date, combustion technology plays an important role in power generation (Broek et al., 1996). Unlike to the conventional coal power generation, it is considered as a carbon-free process as the carbon emitted from biomass combustion are biogenic carbon (Zaimes & Khanna, 2015). In other words, it does not increase the overall carbon amount in the atmosphere. Biomass with high calorific value has the capability to be used as the biomass combustion feedstock. Table 2.2 shows the list of calorific value of various biomass available in Malaysia. However, the low combustion efficiency of biomass (i.e., 35-38 %) is still the major challenge (Bjerg, 2011).

Table 2.2: Calorific value of biomass.

Biomass	Calorific value [kcal/kg]	Reference
EFB	4,000-4,600	(Tian, 2015)
PKS	4,000-4,600	(Tian, 2015)
Rice Husk	3,000	(Zafar, 2015)
Paddy Straw	2,400	(Zafar, 2015)
Sugarcane Bagasse	3,922	(Shukla & Vyas, 2016)

2.3.3 Chemical conversion

Due to the expanding energy demand and the increasing awareness of cleaner production, the interest in finding alternative fuel has been boosted up since 1990s. The oils derived from the oil-bearing crops (usually referred to oilseed) can be served as an alternative fuel. Such crops include coconut, olives, rapeseed, corn seed, oil palm fruit, peanut, etc. Before the oil extraction process, oilseeds are usually being pre-heated. Then, the oilseeds will be crushed and flaked. The flakes are pressed via screw press to recover the oil in the seed. Besides, further extraction presses will be carried out in order to extract more oil from the press cake. However, low combustion efficiency of vegetable oils is the key barrier of this technology (Bandel & Heinrich, 1983).

2.3.4 Summary

The underlying values and potentials of biomass in producing valuable products, either in chemical form or energy form are outlined in this section. This indicates that biomass valorisation is not only environmental-benign but also poses a substantial economic potential. Despite most of the research have shown the economic feasibility of biomass technologies, but most of these evaluations did not account the supply chain cost (transportation cost, management cost, etc.), causing the investors to become hesitate to venture into the biomass industry. Thus, detailed evaluation on economic sustainability (especially transportation cost) have to be conducted.

2.4 Supply Chain Management (SCM)

Supply chain is the network of the entities through which material flows. Those entities include suppliers, carriers, processing hubs, collection centres, retailers and customers (Lummus & Alber, 1997). In other words, all activities associated with moving goods from supplier to the end user, including procurement, production scheduling, order processing, inventory management, transportation, warehousing and customer service are termed as supply chain. In addition, the concept of SCM has been defined as well. Generally, SCM is an integrating philosophy in managing the total flow of a distribution channel from supplier to the end customer (Ellram & Cooper, 1993). It involves the effective and efficiency management of all activities in the supply chain. In fact, SCM plays an important role in cost managing as it is able to monitor or influence the business in supply chain.

2.4.1 Biomass supply chain management (BSCM)

In the past decades, first-generation of biofuels are primarily derived from food crops (e.g., corn, sugarcane) and are mainly utilised in production of biodiesel and bio-ethanol. However, some scholars have argued that the use of food for fuel will lead to a drastic increment in food price (Sharma et al., 2013). To avoid this “fuel vs food” ethical issue, non-food crops (e.g., lignocellulosic biomass, organic residues, algae, microalgae and genetically modified crop which are able to absorb carbon dioxide) has been utilised in the production of second-generation, third-generation and fourthgeneration biofuel (Liew et al., 2014). Thus, development of biomass supply chain management (BSCM) has received a great attention from both academic scholars and industrial players. For instance, Halasz et al. (2005) presented the potential contribution of process network synthesis in "green biorefinery" which converts green biomass to bulk chemical by using P-graph framework. Lam et al. (2013) proposed a two-stage optimisation model to determine the optimal operation and logistics management of palm oil mill biomass in Malaysia. More recently, Paulo et al. (2015) developed a mixed-integer linear programming model to determine the optimal design of the residual forestry biomass to power generation in Portugal. Table 2.3 shows the other recent publication of BSCM.

In general, BSCM concerns the management of biomass and biomass-based products flow within an integrated value chain which contain integrated biorefinery that converts biomass into value-added products or energy (Hong et al., 2016). Hong et al. (2016) point out that there are no district boundaries amongst the four components, i.e., biomass harvesting and management, integrated biorefinery, product distribution and logistics management in BSCM (see Figure 2.2). Due to the continuous increasing economic, environmental and social concerns and external pressures (e.g., governmental policies, societies' preference, etc.), sustainability has grown in prominence for both SCM scholars and practitioners. As a result, the concept of sustainable supply chain management (SSCM) is proposed.

Table 2.3: Recent publication for biomass supply chain management.

Year	Author	Remark
(2008)	Narodoslawsky et al.	Outlined the challenges and opportunities for biomass utilisation industries
(2009)	Rentizelas et al.	Introduced a hybrid modelling approach to identify global optimum for multi-biomass (wheat straw, corn stalks, etc.) tri-generation problem
(2011)	Bai et al.	Proposed a Lagrangian relaxation based heuristic algorithm to solve the nonlinear problem, which integrates biorefinery facility location problem and traffic assignment model.
(2012)	Chen & Fan	Established a two-stage stochastic programming model to explore the potential of biomass-based bio-ethanol production in California.
(2013)	Sun et al.	Presented a two-stage game model to study the optimal strategy for managing a competitive agriculture biomass supply chain
(2013)	Ng et al.	Synthesised an optimal rubber seed supply network which maximise the utilisation of rubber seed oil by using mixed integer linear programming
(2014)	Čuček et al.	Developed an integrated mixed integers linear proamming (MILP) model for multi-period synthesis for biorefinery supply networks
(2016)	Shabani & Sowlati	Presented a hybrid model that integrates a robust optimisation formulation and multi-stage stochastic programming model to account for uncertainties in forest biomass quality and availability.

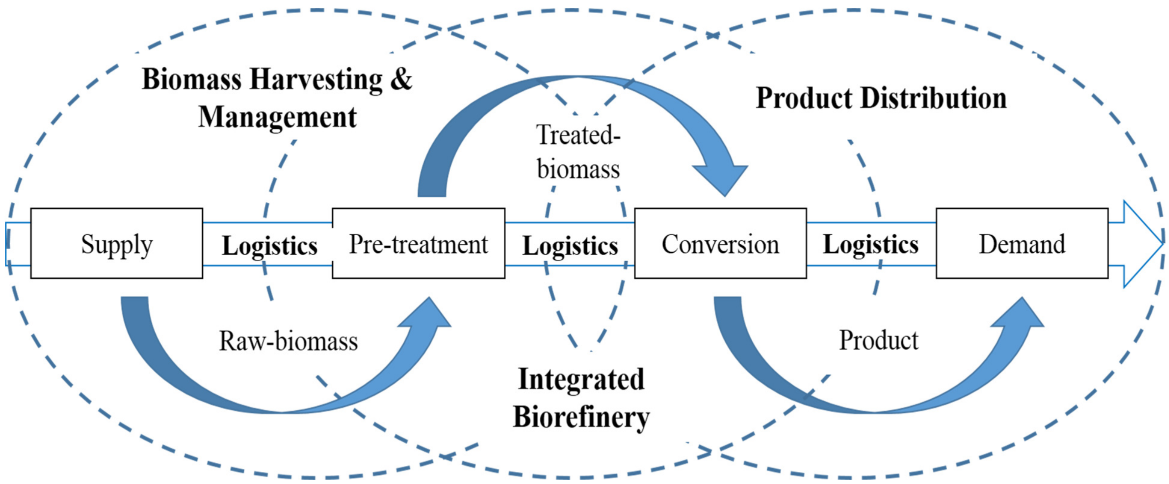

Figure 2.2: Conceptual idea of biomass supply chain (Hong et al., 2016).

2.4.2 Sustainable supply chain management (SSCM)

Sustainable development is defined as "*development that meets the needs of present without compromising the ability of future generation to meet their own needs*" (Brundtland et al., 1987). Sustainable supply chain management (SSCM) concerns of the management of material flows along the entire supply chain while aiming to optimise all three dimensions of sustainable development, i.e., economic, environmental and social (Seuring & Müller, 2008).

Green supply chain management (GSCM) is the early conceptual models of SSCM practices which focused solely on environmental dimension (Marshall et al., 2015). It demonstrates how green technologies and practices can be implemented and in line with the cost minimisation and efficiency optimisation (Lam et al., 2015). The six key features of GSCM are green procurement (practice of purchasing materials and information which provide lower environmental impacts), green manufacturing (manufactured products that utilised clean technologies), green design (research on cleaner production), green marketing (packaging and advertisement of green products), green logistics (logistics management to reduce environmental impacts) and reverse logistics (reuse, recycle, repair or disposal of the green products) (Odeyale et al., 2014). Some of the publications which related to GSCM are listed in Table 2.4.

Table 2.4: Recent publications for green supply chain management.

Year	Author	Remark
(2005)	Sharma and Henriques	Examined the stakeholder influences on the environmental sustainability in the Canadian forestry industry which involves both pollution control and eco-efficiency
(2009)	Mudgal et al.	Presented a hierarchy based model and the contextual relationship among the enablers for the GSCM in India
(2010)	Chen and Chai	Investigated the relationship between attitude towards GSCM
(2013)	Lam et al.	Determined the optimal transportation mode for the palm biomass supply chain in Malaysia which caused a lower CO_2 emission and higher cost-effectiveness
(2014)	Tseng et al.	Developed rigorous quantitative approaches to benchmark the eco-efficiency in GSCM under uncertainty
(2015)	Rostamzadeh et al.	Presented a quantitative evaluation model to measure the uncertainty of GSCM activities and solve the green multi-criteria decision-making problem
(2015)	Tyagi et al.	Identified and analysed the interactions among drivers of implementing GSCM
(2016)	Luthra et al.	Explored the importance of critical success factors to implement GSCM towards sustainability taking into account the automobile industry of India.

During recent decades, SSCM has received great attention from both academic researchers and industries (Ji et al., 2015). Some of the researchers have integrated social sustainability into the evaluation model (see Table 2.5).

Table 2.5: Recent publications for sustainable supply chain management.

Year	Author	Remark
(2001)	Sarkis	Incorporated environmental sustainability into manufacturing strategy and operations
(2008)	Seuring and Müller	Presented a conceptual framework to summarise the research of SSCM
(2012)	Walker and Jones	Developed a typology of approaches to SSCM in order to explore the SSCM issues in companies and to identify the main factors which will influent SSCM
(2013)	Ahli and Searcy	Analysed the published definition of GSCM and SSCM and highlighted the convergences and divergences in the literature as well as their strengths and weaknesses
(2014)	Diabat et al.	Identified the influential enablers for SSCM by using Interpretive Structural Modelling
(2014)	Pagell and Shevchenko	Identified the five main issues that future research has to address in order to help in the development of truly sustainable supply chain
(2014)	Neves et al.	Identified the sustainable practices and measures that are being adopted by organisations in the food industry
(2015)	Ji et al.	Developed a model which adopt the traditional data envelopment analysis method in order to address the issue of eco-design for transportation in SSCM
(2017)	Dubey et al.	Proposed the use of Total Interpretive Structural Modelling in SSCM

The economic sustainability, environmental sustainability and the social sustainability can be measured through various approaches. This is discussed in the subsections below:

2.4.2.1 Economic sustainability

Economic performance is always the key concern in the sustainability evaluation of the business corporation. The key economic indicators which have widely been used in economic evaluation are tabulated in Table 2.6 below:

Table 2.6: Key economic indicators.

Indicator	Description
Gross Profit	Gross profit refers to the profit made after deducting the costs associated with making and selling its products. It is widely used to reflect the core profitability of a company and illustrate the financial successfulness of a given product or service
Net Present Value (NPV)	NPV reflects the present value of cash inflow and cash outflow, which considers the monetary inflation rate over the operational lifespan (Lam et al., 2013)
Benefit-Cost Ratio (BCR)	BCR identifies the relationship between cost and benefits of a proposed project. It can be determined by dividing the present value of benefit by the present value of cost. The proposed project should be rejected if BCR is less than 1 (Kasivisvanathan et al., 2014)
Payback Period (PP)	PP refers to the period of time required to required to recover the total investment cost, or to reach the break-even point. It can be determined by dividing the annualised capital expenditure (CAPEX) by the gross profit (Teo et al., 2017)
Return on Investment (ROI)	ROI evaluates the efficiency and effectiveness of an investment (Deng and Parajuli, 2016). It is measured by dividing net outcome of an investment (can be negative) by the investment cost. The result is expressed as a percentage

2.4.2.2 Environmental sustainability

To-date, a variety of quantitative methods for the evaluation of environmental sustainability are widely available. Most of them were developed based on scoring (Cabezas et al., 1999), benchmarking (Cave & Edwards, 1997) and ranking (Achour et al., 2005).

Life cycle analysis (LCA) is the most scientific reliable method, which was introduced to measure environmental and resource-related products to the production process (Ness et al., 2007). The life cycle concept was firstly proposed by Novick (1960) .It has been modified from life cycle cost analysis to the first waste and energy analysis and eventually become the environmental LCA which is widely used today (Curran, 2012). LCA is commonly referred as a “cradle-to-grave” analysis (Glavic & Lukman, 2007). It covers the system’s entire life cycle from the extraction or harvesting layer to the processing layer (i.e., manufacturing, utilisation, conversion, etc.) and eventually to the post-processing layer (i.e., recycling and disposal), including all transportation and distribution step (Bojarski et al., 2009). With the aid of LCA, environmental impacts caused by the system will be reduced, while will also improve the overall profitability. In general, LCA framework consists of four phases:

I. **Goal and scope definition**: Define the objectives of the analysis and identify the system’s boundaries (e.g., assumptions, limitations, etc.). Note that the goal and scope can be adjusted during the analysis.

II. **Life Cycle Inventory (LCI)**: Collect all the required data (material involved, energy and utilities balance, etc.).

III. **Life Cycle Impact Assessment (LCIA)**: Evaluate the significances of the environmental impacts quantified in the LCI.

IV. **Interpretation**: Evaluate the study systematically by considering the level of completion, degree of consistency and sensitivity analysis. Recommendation and conclusion have to be drawn out in order to highlight those areas that still have space for improvement.

Even though LCA is a well-recognised powerful tool to assess the environmental sustainability, there are still contain some important limitations. For instance, the high level of uncertainty arising from LCI is the main limitation of the LCA method. Besides, numerous LCIA tools exist, each with different methodologies. This might cause result inconsistency of the product analysis (Landis, 2008). Besides, LCA only assesses potential impacts instead of real impacts. Finally, there is still lack of systematic approach for generating LCA solutions (Grossmann & Guillén-Gosálbez, 2010). Some of the review papers for LCA publications are listed in Table 2.7.

Table 2.7: Recent publications for LCA.

Year	Author	Remark
(2013)	Menten et al.	Present the literature of LCA studies estimating advanced biofuels greenhouse gas emissions
(2013)	Muench and Guenther	Synthesise biomass energy LCA that involve biomass electricity and heat generation
(2014)	Huttunen et al.	Provide an overview of the LCA studies on co-digestion biogas production
(2015)	Asdrubali et al.	Harmonise the LCA studies results of renewable energy generation

Table 2.7(cont'): Recent publications for LCA.

Year	Author	Remark
(2015)	Khoo et al.	Quantified the environmental performance of the production of bio-solvent which utilised lignocellulosic feedstock via LCA
(2017)	Hiloidhari et al.	Review the recent application of LCA in understanding the potential impact of bioenergy generation system

Environmental footprints are alternative quantitative measures, which are extensively used to assess the environmental impacts of a process (Čuček et al., 2012a). Footprint refers to a quantitative measurement showing the appropriation of natural sources by humans (Hoekstra, 2008). The key environmental footprints are summarised in Table 2.8.

Table 2.8: Key environmental footprints.

Footprint	Description	Application in BSCM
Carbon footprint (CF)	CF represents the land area for plantation required to absorb the CO_2 (or other greenhouse gases) emitted which will lead to climate change and global warming in the life cycle of product or process (De Benedetto & Klemeš, 2009). Some other indicators which are related to CF have been used in the literatures (e.g., CO_2 footprint (Alireza, 2015), methane footprint (Wiedmann & Barrett, 2011), global warming footprint (Dominguez-Ramos et al., 2015)).	Lam et al. (2010): Developed a regional energy clustering algorithm to minimise the CF of the system Čuček et al. (2012b): Presented a multi-objective optimisation to minimise the CF, at the same time ensuring the economic feasibility Uusitalo et al. (2014): Studied the greenhouse gases released in the life cycle of biogas production Andrić et al. (2015): Assessed the environmental performance of the co-firing power plant based on CF

Table 2.8 (cont'): Key environmental footprints.

Footprint	Description	Application in BSCM
Water footprint (WF)	WF is classified in three categories (Hoekstra & Chapagain, 2005): • Green water footprint: *Consumption of rain water, relevant for agricultural and forestry products* • Blue water footprint: *Consumption of surface or ground water* • Grey water footprint: *Consumption of fresh water required to assimilate pollutants in order to meet the quality standard* In general, WF measures the total volume of fresh water used and/or polluted water generation per unit of time of the process (Galli et al., 2012).	Gerbens-Leenes et al. (2009): Assessed the WF of different bio-energy carriers and fossil energy Čuček et al. (2012c): Evaluated the direct and indirect WF for the bio-energy supply chain model Gerbens-Leenes et al. (2012): Estimated the changes of global water usage which related to the increase demand of biofuel in 2030 Chiu et al. (2015): Determined the WF of second-generation bio-ethanol which derived from bagasse and rice straw Mekonnen et al. (2015): Assessed the WF of the power generation derived from biomass, coal, natural gas, oil, etc.
Energy footprint (ENF)	ENF concerns on the area of forestation required to compensate the total amount of CO_2 emission originating from energy consumption (Palmer, 1998). Vujanović et al. (2014) categories ENF into two: • Electricity-transportation footprint: *Consumption of fuel energy from transportation and consumption/ generation of electricity* • Heat footprint: *Consumption/ generation of heat energy (e.g., combustion, drying, etc..)*	Laude et al. (2011): Assessed the environmental performance of carbon capture and storage system in bio-ethanol production plant based on ENF Chowdhury et al. (2012): Evaluated the life cycle environmental impact of the integrated biodiesel production, including energy consumption for the entire system Vujanović et al. (2014): Evaluated the direct and indirect ENF of a supply network which integrates several renewable energy sources including biomass-based energy

Table 2.8 (cont'): Key environmental footprints.

Footprint	Description	Application in BSCM
Land footprint (LF)	LF concerns on the land demand, i.e., the total land area that are directly and indirectly required to satisfy the consumption (Giljum et al., 2013). The database used for LF calculation is limited to-date.	Khoo (2015): Measured the LF of the bio-ethanol production which derived from different biomass feedstock, i.e., stover, switchgrass, sugarcane bagasse, rice husk and paddy straw
Ecological footprint (EF)	EF is a composite footprint that integrates several footprints (Galli et al., 2012). EF converts impact sources, such as electricity, water, materials, fuel consumption and waste generation into the equivalent land area required to absorb these impacts (Martínez-Rocamora et al., 2016).	Ren et al. (2013): Developed a sustainable bio-ethanol supply chain with a goal of minimising the total EF Wu et al. (2015): Assessed the EF of the integrated biogas production and utilisation system in southern China
Sustainable Process Index (SPI)	SPI is a member of EF family which measures the total area required to embed human activities sustainably into ecosphere (Kettl et al., 2011).	Gwehenberger and Narodoslawsky (2007): Evaluated the environmental impact of bio-ethanol plant based on SPI Stoeglehner and Narodoslawsky (2012): Assessed the environmental performance of biofuels based on SPI

Footprints are often expressed in a unit of area. However, the data expressed in areas units show high variability and high possible errors regarding to the results (Čuček et al., 2012a). Different assumptions were made during the conversion of environmental impacts into land area (Lenzen, 2005). This will increase of uncertainties and lower the reliability of the results (De Benedetto and Klemeš, 2009). Besides, the environmental impacts can be assessed and quantified by its categories (Heijungs et al., 1992). The main categories for environmental impacts are:

- **Global warming potential (GWP)**: Represents the potential change in climate due to the increased concentration of greenhouse gases (GHG), such as CO_2, CH_4, etc. GWP is determined by comparing the infrared absorption rate of a GHG to the infrared absorption rate of CO_2 in a time horizon of 100 years (Young & Cabezas, 1999).

- **Ozone depletion potential (ODP)**: Measures the potential damage in the protective ozone layer. ODP is measured by comparing the reaction rate of an ozone depleting substances (ODS) (e.g., tri-chloro-fluoro-methane (CFC-11), halons, etc.) with the ozone to form molecular oxygen, to the reaction rate of CFC-11 with ozone to form molecular oxygen (Young & Cabezas, 1999).

- **Photochemical ozone creation potential (POCP)**: Represents the potential in forming ground-level ozone or photochemical smog due to the increased concentration of volatile organic compounds (VOCs) (Altenstedt & Pleijel, 2000) and nitrogen oxides (NO_x) (Xiao & Zhu, 2003). POCP is determined by comparing the additional formation of ozone attributed to VOCs (e.g., CO, CH_4) or NOx to the additional formation of ozone attributed to ethene (Andersson-Sköld & Holmberg, 2000).

- **Acidification/ acid-rain potential (AP)**: Measures the acidifying potential of some chemicals (e.g., NO_x, SO_x, etc.), i.e., forming acidifying hydrogen ion (H^+) (Čuček et al., 2015). AP is determined by comparing the rate of releasing

H^+ in the atmosphere as promoted by these chemicals to the rate of releasing H^+ in the atmosphere as promoted by SO_2 (Young & Cabezas, 1999).

- **Eutrophication potential/ Nutrification potential (NP)**: Represents the potentials of eutrophicating substances (i.e., N, NO_x, NH_4^+, PO_4^+, P) and chemical oxygen demand (COD) in causing over-fertilisation of water and soil which can results in increased growth of biomass. NP is expressed in phosphates (PO_4^{3-}) equivalents (Čuček et al., 2015).

- **Aquatic toxicity potential (ATP)**: Shows the maximum tolerance concentration of toxic substances in water by aquatic organisms (Fan & Zhang, 2012). Young and Cabezas (1999) define ATP in the form of LC_{50}, a lethal concentration which caused death in 50% of the *Pimephales promelas* (fish species) within 96 hours.

- **Terrestrial toxicity potential (TTP)**: Shows the maximum tolerance of amount of toxic substances in soil by terrestrial organisms and terrestrial plants. TTP is expressed in the form of LD_{50}, lethal dose which caused death in 50% of rats (Young & Cabezas, 1999).

- **Abiotic depletion potential (ADP)**: Represents the depletion of abiotic raw material (non-renewable resources). ADP is assessed by comparing the extraction rate of each raw material with the reserves of that raw material

(Heijungs et al., 1992). It can be expressed as antimony (Kr) equivalents (Guinée & Heijungs, 1995).

These impact categories have been incorporated in the environmental assessment tools available to-date. For instance, waste reduction (WAR) algorithm is developed to minimise the generation of wastes from a chemical process (Hilaly & Sikdar, 1994). Cabezas et al. (1999) present a generalised WAR algorithm with a potential environmental impact (PEI) balance, which assigned environmental impact values to different pollutants according to their impact categories. WAR algorithm is then further extended to cover the environmental assessment of the energy consumption and generation in the chemical process (Young & Cabezas, 1999). The descriptions of other assessment tools for environmental impacts are tabulated in Table 2.9.

Table 2.9: Other environmental assessment tools.

Method	Description	Impact Categories
Environmental Hazard Index (EHI)	EHI evaluates the overall environmental hazard of chemical process in the early stage of design by ranking the estimated environmental impact of a total release of chemical inventory (Cave & Edwards, 1997).	• TTP • ATP
Eco-indicator 99	It is a damage-oriented approach that evaluates the environmental impacts of the system based on ISO 14040 and ISO 14044 standards (Abbaszadeh & Hassim, 2014). The impact values of each category are combined to a single score, while weight factor is used to indicate the importance of each impact category is the main weakness of this method (Audenaert et al., 2012).	• Human health • Ecosystem quality • Fossil resource

Table 2.9(cont'): Other environmental assessment tools.

Method	Description	Impact Categories
Atmospheric Hazard Index (AHI)	AHI represents the potential catastrophic impact on the atmospheric environment of a total loss of containment in a chemical process (Gunasekera & Edwards, 2003). However, the main drawback of this method is that, it does not cover the environmental impact on soil and water (Abbaszadeh & Hassim, 2014).	• Toxicity • GWP • ODP • POCP • AP
Integrated Environmental Index (IEI)	IEI integrates resource conservation, energy consumption and potential environmental impacts by using analytic hierarchy process (AHP) (Abbaszadeh & Hassim, 2014). Pairwise comparison matrix is constructed according to the relative importance of each criterion (Jia et al., 2004). Again, the assigned values are very subjective.	• Resource and energy consumption • PEI (GWP, ODP, POCP, NP, ATP, TTP) • Human health
IMPACT 2002+	It is an impact assessment methodology, which connect the input and output material inventories in order to determine the impact value of the system (Soo & Doolan, 2014).	• Human health • Ecosystem quality • Climate change • Resource
Inherent Environmental Toxicity Hazard (IETH)	IETH determines the toxicity hazard to the aquatic, terrestrial and atmospheric environment due to a catastrophic failure of a plant (Gunasekera & Edwards, 2006).	• Eco-toxicity (ATP, TTP and AHI)

2.4.2.3 Social sustainability

Social sustainability addresses how social issues can be managed in order to ensure the long-term survivability of the organisation (Mani et al., 2015). However, social sustainability has seen less attention compared to environmental sustainability. The main reason reported in the literatures is that the conceptual clarity for social sustainability is still unclear (Gopal & Thakkar, 2016). To-date, several social sustainability dimensions have been explored by the academicians and practitioners. Some of the key social indicators are listed below, while other social assessment tools are summarised in Table 2.10.

- **Health and Safety**: Health and safety is one of the key indicators for the social sustainability of supply chain (Mani et al., 2014). Carter and Jennings (2000) emphasized that the safety of transportation and warehousing operations have to be considered in the evaluation of social sustainability. In the recent publication, Saunders et al. (2015) report that early supplier engagement on the worker safety issue has a positive correlation with the social sustainability performance of the organisation.

  To-date, there are plenty of quantification techniques for inherent safety and occupational health. Prototype Inherent Safety Index (PIIS) which initially proposed by Edward and Lawrence (1993) is one of the pioneering safety indices. PIIS is intended for analysing the different alternative of process routes and evaluating them based on an integrated chemical score, which consists of inventory, flammability, explosiveness and toxicity. PIIS is then extended to Inherent Safety Index (ISI), which covers corrosion, side reactions, offside battery limit area, etc. (Heikkilä, 1999). Subsequent scholars focused on the improvement of the inherent safety quantification technique, such as Process Route Index (PRI) by Leong and Shariff (2009) and Process Stream Index (PSI) by Shariff et al. (2012). For inherent health assessment, Johnson (2001) had introduced a comprehensive index, called Occupational Health Hazard Index (OHHI). However, the main weakness of OHHI is the low accuracy of the estimation for fugitive emission that only consider from one sample connection (Hassim, 2012). Therefore, OHHI is further modified and improved as Process Route Healthiness Index (PRHI). PRHI is influenced by health impacts due to chemical releases and the airborne chemicals inhaled by workers (Hassim & Edwards, 2006). Although PRHI offers a lot of benefits, it is not suitable to be used at the preliminary stage as it required ample of information to assess all the factors considered in PRHI (i.e., Inherent Chemical and Process Hazard Index (ICPHI), Health Hazard Index (HH), Material Harm Index (MH), Occupational Exposure Limit (OEL) and Worker Exposure Concentration (WEC)) (Hassim, 2012). In order to address this issue, Hazard Quotient Index (HQI), which is able to quantify worker's health risk based on fugitive emissions in a relatively simple way is proposed (Hassim & Hurme, 2010). Young and Cabezas (1999) suggested to evaluate the health aspect of a system by using human toxicity potential, i.e., human toxicity potential by ingestion (HTPI) and human toxicity potential by either inhalation or dermal exposure (HTPE). More recently, Wan et al. (2016) has considered workplace footprint (WPFP) to measure the work-related casualties of the sago value chain. WPFP can be determined based on (i) reported lost days of work per unit of products (De Benedetto & Klemeš, 2009); or (ii) statistical fatality rate per unit of economic activity (Wan et al., 2016).

- **Equity**: All job applicants should be treated equally without denying privileges and rights of them merely based on gender, religion, race, age and nationality (Mani et al., 2016). Clair et al. (1997) described the importance of the gender, racial and religious diversity in the workplace. This has been further proved in the more recent publications. For instance, Mazalliu and Zogjani (2015) and the report conducted by Asian Development Bank (2015) shows that the increase of female labour force participation (FLFP) in the workplace can be beneficial to the organisations.

- **Ethical responsibility**: Notable contributions from the research done by Husted and Allen (2000), Hemingway (2005), Gunasekaran and Spalanzani (2012) suggested that integrating ethical principles in supply chain practices is essential for the success of sustainability initiative. Ethical supply refers to the practice of providing goods and services to the customers while considering the engineering ethics (Beamon, 2005). Therefore, supply chain member should not engage in unethical practices such as bribery, coercion, pollution, etc. (Chardine-Baumann & Botta-Genoulaz, 2014). Mani et al. (2016) emphasised that the supply chain managers should not use hazardous or sub-standard raw material for production nor selling them to the customers.

- **Labour rights/ Child and bonded labour**: During the past decades, more attention has been directed toward the human rights issues, labour rights issues and other social issues such as the presence of forced labour and child labour. Emmelhainz and Adams (1999) highlighted the importance of protecting human and labour rights in the SCM. Lately, Mani et al. (2016) suggested that companies should respect human rights, stop using sweat shop labour, provide reasonable working wages to the employees, support the prohibition of child labour.

- **Philanthropic responsibility**: Some of the companies often take part in philanthropic activities, such as charity, renovation of school and provide educational opportunities and employment training for local youth (Mani et al., 2016). Hutchins and Sutherland (2008) measured the company's philanthropic commitment by using the ratio of the charitable contributions to its market capitalization. In India, a company law even stated that companies are responsible to give away at least 2 % of their net profits to charity (Balch, 2016).

- **Society**: Several indices have been developed to investigate the effect of SCM practice or company on the community. For instance, poverty footprint (POF) is proposed to assess the companies' effect on people living in poverty (Čuček et al., 2015). With the aid of POF, company can ensure a positive effect on the people who live in poverty (e.g., job creation, cleaner production with less pollution generated, etc.) (Oxfam International, 2009). In addition, "fuel vs food" ethical issue can be expressed as food-to-energy footprint (FEF). Numerous scholars have proven that the commercialisation of production of fuel from food crop will lead to an expansion in the amount of food crops being diverted away from the global food market, resulting in undesirable rise of food price (Asch & Heuelsebusch, 2009). However, since year 2008, there is no common trend between increasing biofuel production and rising food prices (EC, 2011). Thus, it is still lack of evidence to prove the relationship between these two components.

- **Regulatory responsibility**: All activities embed in the SCM must comply with legal requirement which established by the community (Hutchins & Sutherland, 2008). For instance, SCM members have to ensure the environmental performance and safety features of the chain do meet the requirement set by regulations such as ISO 14001 (ISO 14001:2015, 2015), Environmental Quality Act 1974

(Environmental Quality Act, 1974), Occupation Safety and Health Act 1994 (Occupational Safety and Health Act, 1994), etc.

Table 2.10: Social sustainability assessment tools.

Method	Description	Publications
Corporate Social Responsibility (CSR)	CSR is a company's initiatives to assess and take responsibility for the company decisions which contribute effects on environmental and social dimensions (Lau, 2011). It can be further categorised into four groups, i.e., economic responsibilities, regulatory responsibilities, ethical responsibilities, philanthropic responsibilities (Carroll, 1979).	Beamon (2005): Applied the concept of CSR to solve the ethical decision-making in SCM Joseph et al. (2016): Conducted a CSR studies which focusing on the anti-corruption practice, and the correlation between the level of corruption and economic growth
Purchasing Social Responsibility (PSR)	PSR referred to the CSR in purchasing, i.e., the involvement of purchasing function on socially responsible logistics (e.g., avoid procurement of hazardous material, ensure workers' safety, etc.) advocated by stakeholders (Carter & Jennings, 2002). According to Carter and Jennings (2004), environmental purchasing which aimed to facilitate recycling, reuse and resource reduction can be categorised as PSR practice.	Carter (2005): Showed that the overall business cost can be minimised by improving the suppliers' performance via PSR adoption Ciliberti et al. (2008): Summarised the most relevant PSR practices (e.g., educate suppliers, monitor suppliers' behaviour, ethical management, verify safety condition of workplace, etc.)
Logistical Social Responsibility (LSR)	LSR refers to the socially responsible management of supply chain under a cross-functional perspective (Carter & Jennings, 2000). In general, LSR can be defined as a sub-concept of SSCM (Palaniappan et al., 2004).	Carter and Easton (Carter & Easton, 2011): Incorporate LSR practice into SCM with consideration of several social issues (i.e., business ethics, gender diversity, safety, human rights, equity and philanthropic responsibility)

2.4.3 Summary

This section summarises the available techniques to evaluate sustainability performance in terms of environmental and social dimensions. However, only few works but only few works have considered and integrated all three sustainability dimensions (i.e., economic, environmental and social dimension) into the optimisation model of a biomass supply chain. Therefore, additional efforts have been conducted in this thesis to develop an optimisation model which aims to optimise these three sustainability dimensions simultaneously.

2.5 Optimisation Techniques for Supply Chain Management (SCM)

In the conventional SCM, the design of the supply chain network (SCN) is merely focusing on a single objective optimisation, i.e., either minimise cost or maximise profit. However, the real-life design, planning and scheduling of task usually involve different objective functions that might be contradictory to each other. Many techniques and approaches have been proposed and applied in order to solve the synthesis problem of SCN. Generally, it can be classified into three types, i.e., mathematical modelling, multi-agent technology and heuristic algorithm.

2.5.1 Mathematical modelling

In mathematical modelling, the problem will be represented by a mixed-integer programming (MIP) or MILP. Usually, these can be solved by using the conventional ε-constraint method (Guillén et al., 2005a). The main benefit of using traditional mathematic programming is that the optimum solution can always be found. However, it is not capable to solve the real-time optimisation of large-scale problem, which are often fuzzy (Paksoy et al., 2012). The required computation time will increase significantly when the problem sizes increases. The list of works, which implemented mathematical modelling technique to solve SCM problem, are tabulated in Table 2.11.

Table 2.11: Mathematical programming in supply chain management.

Year	Author	Remark
(1998)	Robinson and Satterfield	Developed a multidisciplinary framework that considers the interactions among firm's distribution strategy, market share and cost
(1998)	Petrovic et al.	Proposed a supply chain fuzzy model to analyse the behaviour of a serial supply chain in an uncertain environment
(1999)	Dogan and Goetschalckx	Developed a mixed integer programming formulation and an integrated design methodology based on primal decomposition
(1999)	Li and O'Brien	Proposed an integrated decision model for assessing potential partners in a supply chain
(2000)	Lee and Kim	Proposed a hybrid simulation approach which is a specific problem-solving procedure to solve the production distribution problem
(2001)	Jayaraman and Pirkul	Developed a heuristic procedure to solve the integrated logistic model in a multi-echelon environment
(2002)	Syam	Extended the traditional location models by introducing several logistic components
(2002)	Cakravastia et al.	Developed an analytical model of the supplier selection process in designing a supply chain network
(2003)	Jayaraman and Ross	Solved the new combinatorial problem that incorporates cross-docking in supply chain environment by using simulated annealing methodology
(2003)	Yan et al.	Proposed a strategic production-distribution model for supply chain design with consideration of bills of materials

Table 2.11(cont'): Mathematical programming in supply chain management.

Year	Author	Remark
(2004)	Amaro and Barbosa-Póvoa	Proposed a discrete model to ease the decision-making process at the operation level of industrial supply chain
(2004)	Erol and Ferrell	Developed an integrated methodology to solve two fundamental decisions making, i.e., assigning suppliers to warehouse and warehouse to customer
(2004)	Chen and Lee	Proposed a multi-product, multi-stage and multi-period scheduling model to deal with multiple incommensurable goals for a multi-echelon SCN
(2005)	Amaro and Barbosa-Póvoa	Introduced a new continuous-time mathematical formulation for the optimal schedule of industrial supply chains
(2005)	Ryu	Developed a multi-level programming framework in capturing complex supply chain decision making processes
(2005)	Graves and Willems	Proposed a two-state dynamic model to minimise the total supply chain cost which includes cost of goods sold, safety stock cost and pipeline stock cost
(2005a)	Guillén et al.	Developed a two-stage stochastic model to take into account of the effect of uncertainty in production
(2006)	Amiri	Presented a computational study in investigating the value of coordinating production and distribution planning
(2006)	Liang	Developed an interactive fuzzy multi-objective linear programming method for solving the transportation problems
(2008)	Guo and Tang	Proposed an evaluation model to analyse the feasibility of planning by comparing the planned cost with the anticipated cost

Table 2.11(cont'): Mathematical programming in supply chain management.

Year	Author	Remark
(2008)	Liang	Developed a fuzzy multi-objective linear programming model with piecewise linear membership function to solve the integrated multi-product and multi-period production/ distribution planning problem
(2009)	Peidro et al.	Proposed a fuzzy mathematical programming model for supply chain planning which considered process uncertainties
(2010)	Franca et al.	Introduced a multi-objective stochastic model that used Six Sigma to evaluate the financial risk in supply chain
(2010)	Xu and Zhai	Used fuzzy number to depict customer demand and investigated the optimisation of the vertically integrated two-stage supply chain under different scenario
(2012)	Paksoy et al.	Developed a fuzzy multi-objective programming model to minimize the total transportation cost
(2012)	Seifert et al.	Developed a model for three-echelon supply chain with price-only contracts
(2012)	Afshar and Haghani	Proposed a mathematical model that controls the flow of commodities from sources through the supply chain and finally to the recipients
(2012)	Li and Womer	Developed a mathematical model to optimise the sourcing and planning decision simultaneously while exploiting their trade-offs
(2013)	Ramezani et al.	Proposed an evaluating method to evaluate the systematic supply chain configuration maximizing the profit, customer responsiveness and quality as objectives of the logistic network
(2013)	Lam et al.	Developed a two-stage optimisation model to determine the optimal operation and logistics management of the waste

Table 2.10(cont'): Mathematical programming in supply chain management.

Year	Author	Remark
(2013)	Ng et al.	Synthesised an optimal rubber seed supply network which maximise the utilisation of rubber seed oil by using mixed integer linear programming
(2014)	Ng et al.	Introduced disjunctive fuzzy optimisation approach to determine the optimum pathways in the bioenergy-based plant.
(2014)	Ng and Lam	Developed a functional clustering approach integrated in an industrial resources optimisation
(2015)	Jeng	Developed a causal model of the factors that influence supply chain collaboration
(2015)	Ng et al.	Proposed a novel algebraic technique for supply network synthesis and analysis which allows concurrent set-up of material allocation

2.5.2 Multi-agent technology

Multi-agent technology is another common technique which firstly introduced by Swaminathan et al. (1998). By using this technique, supply chain is structured as a library of structural elements (i.e., production and transportation) and control elements (i.e., flow, inventory, supply and demand). All of them are represented by agents that interact with each other in order to determine the optimal configuration. The major strength of this technique over the conventional mathematical modelling is its flexibility. It is able to interpret new information from time to time, allows exchange between agents and enables new policies (Ahn et al., 2003). However, finding an appropriate methodology to coordinate the agents is still a major challenge. Table 2.12 shows the list of publication, which utilised multi-agent technology in SCM.

Table 2.12: Multi-agent technology for supply chain management.

Year	Author	Remark
(2000)	Fox et al.	Investigated the issues and present the solutions for the construction of agent-oriented software architecture
(2003)	Kaihara	Formulated the SCM as a discrete resource allocation problem with dynamic environment
(2005)	Fischer and Gehring	Developed a multi-agent system for supporting of transhipments of imported finished vehicles
(2005b)	Guillén et al.	Applied an agent-oriented simulation system to model each entity in supply chain as an independent agent
(2006)	Lin and Lin	Introduced multi-agent negotiation mechanism to solve the distributed constraint satisfaction problem
(2006)	Zhang et al.	Proposed an agent-based approach to integrate, optimise, simulate, restructure and control the supply network dynamically and cost effectively
(2007)	Zhang and Zhang	Developed an agent-based model of consumers purchase decision-making which combines consumers' psychological personality and the interactions in market
(2008)	Forget et al.	Proposed a multi-behaviour planning agent model using different planning strategies when decisions are supported by a distributed planning system
(2011)	Giannakis and Louis	Developed a framework for the design of a multi-agent based decision support system and risk mitigation in supply chain management
(2014)	Sitek et al.	Introduced the concept of hybrid multi-agent approach for the modelling and optimisation of supply chain management
(2015)	Fu and Fu	Developed a new intelligent system framework of adaptive multi-agent system to improve the cost collaborative management in supply chain

2.5.3 Heuristic algorithm

To overcome the coordination problem faced by multi-agent approach, Akanle and Zhang (2008) proposed a heuristic algorithm, called genetic algorithm (GA), to dynamically solve the supply chain synthesis problem. During the past few decades, GA has often been implemented to solve single-objective and multi-objective optimisation problem in production and operational management that are NP-hard. Recently, GA technique has been modified to suit each specific problem. The publications which related to GA implemented in SCM are listed in Table 2.13.

Another technique which also has been widely used is ant colony optimisation (ACO) meta-heuristic. This technique is one of the nature-inspired meta-heuristics that mimics the behaviour of ant colonies and the evaporation effect of the pheromones during their food search process. Despite that optimum solution is not guaranteed, it provides a useful compromise between the amount of computation time necessary and the quality of the approximated solution space (Moncayo-Martinez & Zhang, 2011). ACO was initially used to solve the decision-making problems which involve only single objective function (Bullnheimer et al., 1999). Recently, it had been proven that ACO is capable to solve many real-world problems efficiently and effectively. Table 2.14 shows the list of works which implemented ACO technique in SCM.

On top of that, another swarm-based optimisation model, or Bee Algorithm (BA) has been introduced by Pham and Ghanbarzadeh (2005). Similar to ACO, BA is also a nature-inspired heuristic. BA is actually an algorithm that mimics foraging behaviour of honeybees to find the best source of food. Recently, BA has proven to be a more powerful optimisation tool, which able to determine better Pareto solutions for the SCN synthesis problem compared with the ACO technique (Mastrocinque et al., 2013). A list of publications, which applied BA in SCM are tabulated in Table 2.15.

Table 2.13: Genetic algorithm (GA) for supply chain management.

Year	Author	Remark
(2002)	Syarif et al.	Developed a spanning tree-based GA to solve the logistic system design in supply chain
(2005)	Gen and Syarif	Proposed a spanning tree-based GA to solve the production and distribution problem in supply chain with the aim of minimizing the cost
(2005)	Truong and Azadivar	Proposed a methodology which integrated mixed integer programming and genetic algorithm to determine the optimal configuration of a supply chain
(2009)	Yun et al.	Developed a GA approach with adaptive local search scheme to effectively solve the multistage supply chain problem
(2009)	Altiparmak et al.	Proposed a solution procedure based on steady-state GA with a new encoding structure for the synthesis of a single-source, multi-product and multi-stage SCN
(2010)	Zegordi et al.	Developed a gendered GA which considered two different chromosomes with non-equivalent structure to solve the two-stage supply chain optimisation problem
(2010)	Kannan et al.	Solved the multi-echelon, multi-period closed loop supply chain model by using GA
(2011)	Yeh and Chuang	Developed an optimum mathematical planning model for green partner selection by using GA
(2014)	Bandyopadhyay and Bhattacharya	Modified the non-dominated sorting GA to solve the tri-objective supply chain problem
(2015)	Pasandideh et al.	Utilised non-dominated sorting GA and non-dominated ranking GA to solve the multi-product, multi-period three echelon supply chain problem

Table 2.14: Ant colony optimisation (ACO) for supply chain management.

Year	Author	Remark
(2009)	Silva et al.	Introduced ACO technique to solve the SCM
(2009)	Wang	Developed a two-phase ant colony algorithm to solve the multi-echelon defective SCN design
(2009)	Wang and Chen	Proposed an ant algorithm to solve a set of non-linear mixed integer programming models for supply chain
(2011)	Moncayo-Martínez and Zhang	Proposed a Pareto ACO to solve the multi-objective supply chain design problem
(2013)	Moncayo-Martínez and Zhang	Proposed a modified ACO which utilised a bi-objective MAX-MIN function to solve the supply chain problem
(2014)	Moncayo-Martínez and Recio	Determined a set of supply chain configurations by using the Pareto ACO
(2015)	Cheng et al.	Proposed an improved ACO to solve the scheduling problem for the production in supply chain
(2015)	Wang and Lee	Proposed a revised ACO to improve the original ant algorithm by using efficient greedy heuristic to solve the supply chain problem

Table 2.15: Bee Algorithm (BA) for supply chain management.

Year	Author	Remark
(2010)	Koc	Improved the BA using combined neighbourhood size change and site abandonment strategy
(2013)	Mastrocinque et al.	Proposed BA in dealing with multi-objective supply chain model to find the optimum configuration which minimise the total cost and total lead time
(2013)	Teimoury and Haddad	Implemented BA to solve the parallel batch production scheduling in a supply chain

Table 2.15(cont'): Bee Algorithm (BA) for supply chain management.

Year	Author	Remark
(2013)	Chen and Ju	Proposed a novel artificial bee colony algorithm for solving the mixed-integer nonlinear SCN model
(2014)	Yuce et al.	Developed an enhanced BA with adaptive neighbourhood search and site abandonment strategy to solve the multi-objective supply chain model
(2014)	Zhang et al.	Proposed the hybrid artificial bee colony algorithm to solve the environmental vehicle routing problem with minimisation of overall travel distance and travel time

2.5.4 P-graph framework

P-graph framework was initially introduced by Friedler et al. (1992a) and has been widely implemented in the systematic optimal design, including industrial processes synthesis and supply chain network synthesis. This framework has three components: (i) P-graph representation of processing networks; (ii) axioms which must be satisfied for the combinatorial feasible solution structures; and (iii) algorithms which capable to determine the maximum structure, solution structures and the optimal structure. Maximal structure of P-graphs is similar to super-structure of a simple directed graph, but in addition, maximal structure is mathematically rigorously defined (Friedler et al., 1993). Solution structure referred to each possible process pathway in the process network synthesis problem while optimal structure is the most preferable solution structure (normally in economic perspective). P-graphs are bi-partite graphs, which has two kinds of vertices (M-type and O-type). The M-type or material type vertex represents material and energy streams in a system such as raw materials, intermediates and products; whereas O-type or operating unit type vertex represents the operating units in the network (e.g., machine, transportation mode, etc.). The numbers on arcs indicate the conversion rate of the process. Figure 2.3 represents a P-graph with the following operating units O1, O2 and O3 and following materials M1, M2, M3, M4, M5 and M6. The circle notes with triangle inscribed (i.e., M1, M2 and M3) are raw materials; the circle with another embedded circle (i.e., M5) is referred to product; while the solid-filled circle (i.e., M4) is intermediate.

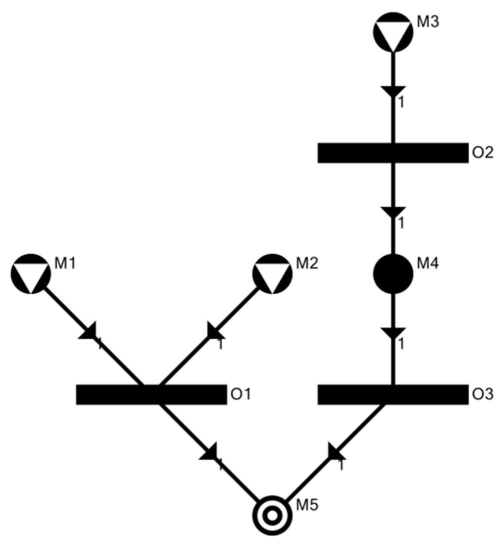

Figure 2.3: P-graph illustration.

The P-graph method follows five axioms to help determine the differences between vertices and to generate solution structures (Friedler et al., 1992b):

I. Every demand is represented in the structure.

II. A material represented in the structure is a resource if and only if it is not an output from any operating unit represented in the structure.

III. Every operating unit represented in the structure is well-defined.

IV. Every operating unit represented in the structure has at least one directed path leading to the product.

V. If a material belongs to the structure, it must be an input or an output from at least one operating unit represented in the structure.

Moreover, three effective algorithms have been developed based on these five axioms: maximal structure generator (MSG), solution structure generator (SSG) and accelerated branch-and-bound (ABB) algorithm. MSG generates a mathematically rigorous superstructure of the system, which shows all possible connections in producing the products. SSG generates all combinatorially feasible solutions based on MSG, whereas ABB determines the optimal solution based on the solution structures generated from SSG, in conjunction with additional information (e.g., flow, monetary value, etc.). It is worth to note that ABB is more efficient for optimization since the available information from MSG and SSG are used to dramatically reduce the size of the search space, as compared to conventional branch-and-bound algorithm (Lam, 2013). In addition, another attractive feature of P-graph framework is its capability to determine optimal and sub-optimal solutions simultaneously (Lam et al., 2016).

Initially, P-graph method consists of two separate software: PNS Draw and PNS Studio. PNS Draw is used to construct the problem structure by defining the connections between each material and operating unit, while PNS Studio is used to enter measurement units, constraints, costs and prices of material streams and operating units. In order to increase the ease of use, the developers of P-graph framework have introduced an integrated version of the two software, called P-graph Studio (P-Graph Studio, 2017).

Recently, the applications of P-graph are getting extended to several fields, including synthesis of azeotropic distillation system (Feng et al., 2003), reaction pathway identification (Fan et al., 2012), logistics design (Barany et al., 2011), evacuation route planning (García-Ojeda et al., 2013), retrofit planning (Chong et al., 2014), supply chain management (Lam, 2013), etc. Other publications related to the use of P-graph approach in SCM are tabulated in Table 2.16.

Table 2.16: Applications of P-graph approach in supply chain management.

Year	Author	Remark
(2009)	Fan et al.	Introduced P-graph to synthesise an optimal and sub-optimal options for the supply chain system
(2011)	Sule et al.	Extended the algorithms and software of P-graph for generating optimal and near-optimal supply network with given reliability of each production option
(2011)	Barany et al.	Proposed P-graph framework in solving vehicle assignment problem in a supply network
(2012)	Kalauz et al.	Proposed extended P-graph methodology, algorithm and software to improve supply networks where quality is measured by cost and response time
(2013)	Bertok et al.	Revealed a methodology to model the supply chain as well as to synthesise optimal and alternative solutions while taking into account of structural redundancy
(2013)	Lam	Demonstrated the extension of P-graph via case studies in supply chain systems, carbon emission reduction system and cleaner production process synthesis

Table 2.16(cont'): Applications of P-graph approach in supply chain management.

Year	Author	Remark
(2013)	Vance et al.	Proposed a computer-aided methodology for designing a sustainable energy supply chain by using P-graph
(2014)	Tan et al.	Proposed P-graph approach to determine the optimal operational adjustment in the poly-generation plants

2.5.5 Summary

This section presents the available optimisation techniques which widely used to optimise the supply chain problem. However, most of the previous works did not consider physical capacity limits of the vehicles (i.e., volume and weight) in their proposed transportation design models. For instance, Ng et al. (2013) utilise a generalise cost factor [RM/km/t] to calculate the overall transportation required for the proposed palm biomass supply chain without considering the vehicle capacity constraint; Bertazzi and Maggioni (2014) determine the service zone of a stochastic capacitated traveling salesmen location problem that minimise the expected cost of the travelled routes without including the vehicle capacity constraint into the model; Király et al. (2015) solves the multiple traveling salesmen problem without considering the capacity limit of vehicle by using a multi-chromosome based genetic algorithm. However, none of them has developed a user-friendly tool for the decision-makers in order to improve the effectiveness of the decision-making process. Therefore, there is a need to develop a transportation decision model which consider vehicle capacity constraint. In addition, most of the aforementioned methods (exclude P-graph approach) are heavy-reliance of programming knowledge of the users, causing difficulties for the decision-makers which do not have strong programming background. In order to mitigate the gaps between the researchers and industry players, the decision-making tools developed in this thesis should be developed in a way that it is user-friendly, easy to understand and non-programming-background dependent.

2.6 Identification and Debottlecking of Multi-Biomass Supply Chain

The problem of identifying bottlenecks and subsequently debottlenecking them is another significant topic of research.

2.6.1 Bottlenecks in biomass supply chain

The term "bottleneck" is defined differently by various researchers. Notably, Goldratt and Cox (1984) defined bottlenecks as "*the critical path in a system that limit the makespan of the schedule*". Carlie and Rebai (1996) had defined bottleneck as "*a machine on which jobs have higher processing times than on others*". Lately, Beer (2015) had proposed a generalised definition for bottleneck, i.e., "*the element that limits the system in attaining higher throughput beyond a certain threshold*". However, the term "bottleneck" should not be limited to economic-related barriers (e.g., throughput (Beer, 2015), makespan (Goldratt & Cox, 1984), process efficiency (Carlier & Rebai, 1996)) but also related to other environmental-related barriers (concern on environmental risks, e.g., extensive land requirement (Oh et al., 2010), extensive emission of toxic gas (Asadullah, 2016), massive water requirement (Wattana, 2014), etc.) and social-related barriers (restriction on social factors, e.g., exposure to various social risks (Yatim et al., 2017), lack of domestic support (Foo, 2015), low social awareness (MIGHT, 2013), etc.). All these compounded issues are certainly hindering the development of the biomass industry, as the demand of biomass-derived products is dependent on public adoption, market acceptance and consumer behaviour (Karytsas

& Theodoropoulou, 2014). Other cited bottlenecks of biomass industry in Malaysia are summarised in Table 2.17.

Table 2.17: List of cited bottlenecks for biomass industry in Malaysia.

Barriers	Barriers Description	References
High logistic cost	Due to the low mass density of biomass, it required an extensive amount of volume per mass ratios for storage and transportation. This problem is further aggravated by the remote location of biomass sources in Malaysia.	(MIGHT, 2013) (Asadullah, 2016)
Capital intensive	Depending on the biomass feedstock, the operational components starting with the construction of the plant and facility, implementation of technology, adoption of techniques to logistics arrangement contributed to high setup cost for the industry.	(Tang et al., 2012) (Ortas et al., 2013)
Lack of public awareness	Without proper awareness, end user will not consider the environmental cost in purchasing and procurement decision. Therefore, lead to low domestic market support of green products.	(Zainul-Rashid, 2010) (MIGHT, 2013)
Financing gaps in local financing framework	As biomass industry is relatively new in Malaysia and exerting unique risk profile, financial institutions have neither experience nor adequate knowledge about the industry. By maintaining the traditional lending structure and conventional risk assessment in making credit decision tend to be resulting in jeopardising the bankability of biomass-related projects, in the worse cases.	(Beck & Martinot, 2004) (Bai et al., 2014)
Unwillingness of suppliers in long-term commitment	Without the assurance of long-term supply agreement from the suppliers, potential investors and industry players are not able to make an accurate economic analysis for the biomass business.	(Rogelio & Soon, 2010) (MIGHT, 2013)

Table 2.17 (cont'): List of cited bottlenecks for biomass industry in Malaysia.

Barriers	Barriers Description	References
Lack of domestic market support	The weak institutional promotion and advertisement, poor perception from the community and minimal domestic market support are the crucial issues which retard the commercialisation progress of biomass industry	(Rosmiza et al., 2015) (Foo, 2015) (Sun & Feng, 2012)
Exposure to various risks	Lack of understanding of risks associated with the biomass industry is one of the reasons for the industry's slow growth. These risks include financial risk, business risk, regulatory risk, technology risk, and supply chain risk.	(Johari et al., 2015) (Yatim et al., 2016) (Yatim et al., 2017)
Lack of biomass monitoring and tracking system	It is very important for the stakeholders in their assessments of the biomass business initiatives. Yet, the supply chain traceability in Malaysia remains at the least level.	(Rogelio & Soon, 2010) (MIGHT, 2013) (NEPCon, 2016)
Green barriers	Despite the green benefits that have been extensively highlighted by the scholars, community has started to argue around the sustainability performance of the "green technology".	(MIGHT, 2013), (Foo, 2015), (Asadullah, 2016)

2.6.2 Debottlenecking methods for biomass supply chain management (BSCM)

The term "debottlenecking" is defined differently at different phases of supply chain development (see Figure 2.4). Most of the previous works focus on debottlenecking at operational-phase which design of a system or a plant is already existed. Debottlenecking at this phase is defined as "*a strategy of achieving desired performance of a system or plant (e.g., higher yield, purity or productivity), which is currently incapable of with the current design*" (Schneider, 1997). For instance, Alshekhli et al. (2010) used a computer-aided process simulation tool to identify possible debottlenecking strategies in a cocoa manufacturing plant for higher profitability and productivity. More recently, Kasivisvanathan et al. (2014) had introduced a heuristic framework for identifying and removing process-oriented bottlenecks (bottlenecks which restrict throughput, yield or efficiency) in a palm oil-based integrated bio-refinery.

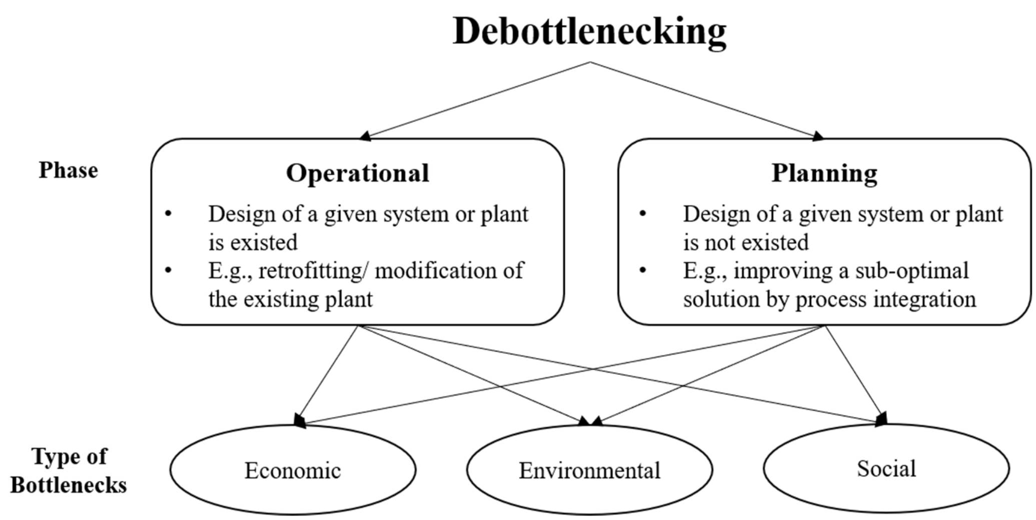

Figure 2.4: Debottlenecking at difference phases.

On top of that, various efforts have been devoted in developing a bottleneck detection approach. For instance, bottleneck can be targeted by measuring the (i) average time and recognising the machine with the longest waiting time to be the bottleneck and (ii) average workload and recognising the machine with largest workload as the bottleneck (Law & Kelton, 1991). More recently, Roser et al. (2001) proposed a bottleneck detection method which able to identify bottlenecks by measuring the longest average consecutive active duration of machines (time required for operation, maintenance, instalment, etc.).

Despite the decent contributions of the aforementioned works, none of them has considered the debottlenecking at planning-phase which configuration of a system or a plant is yet to be designed. At this phase, debottlenecking refers to the "*process of revealing root causes that made a given solution become unpreferable, and subsequently revamping it to improve its overall preferability*". The debottlenecking at this preliminary stage of design is vital for the better understanding of the potentials embedded in each solution (technology selection, logistics management, operation strategy, etc.), which enables accurate decision-making in selecting appropriate technologies or designs to ensure business sustainability (Foo, 2017). The conceptual illustration of debottlenecking at planning phase is demonstrated in Figure 2.5.

As illustrated, pathway II is less preferable due to the low sustainability performance for the secondary process. However, the optimality of the sub-optimal solution can be improved by removing bottlenecks via implementation of appropriate strategies (e.g., process integration, heat integration, emission abatement planning, regulatory policy amendment, etc.). Thus far, limited debottlenecking method capable to identify diverse form of bottlenecks. Therefore, the concept of bottlenecks should not be restricted in economic dimension, but have to be extended to cover the other two sustainability dimensions (i.e., environmental and social). Aside from this, more effort has to be made in order to develop a novel bottleneck detection method which able to identify these bottlenecks.

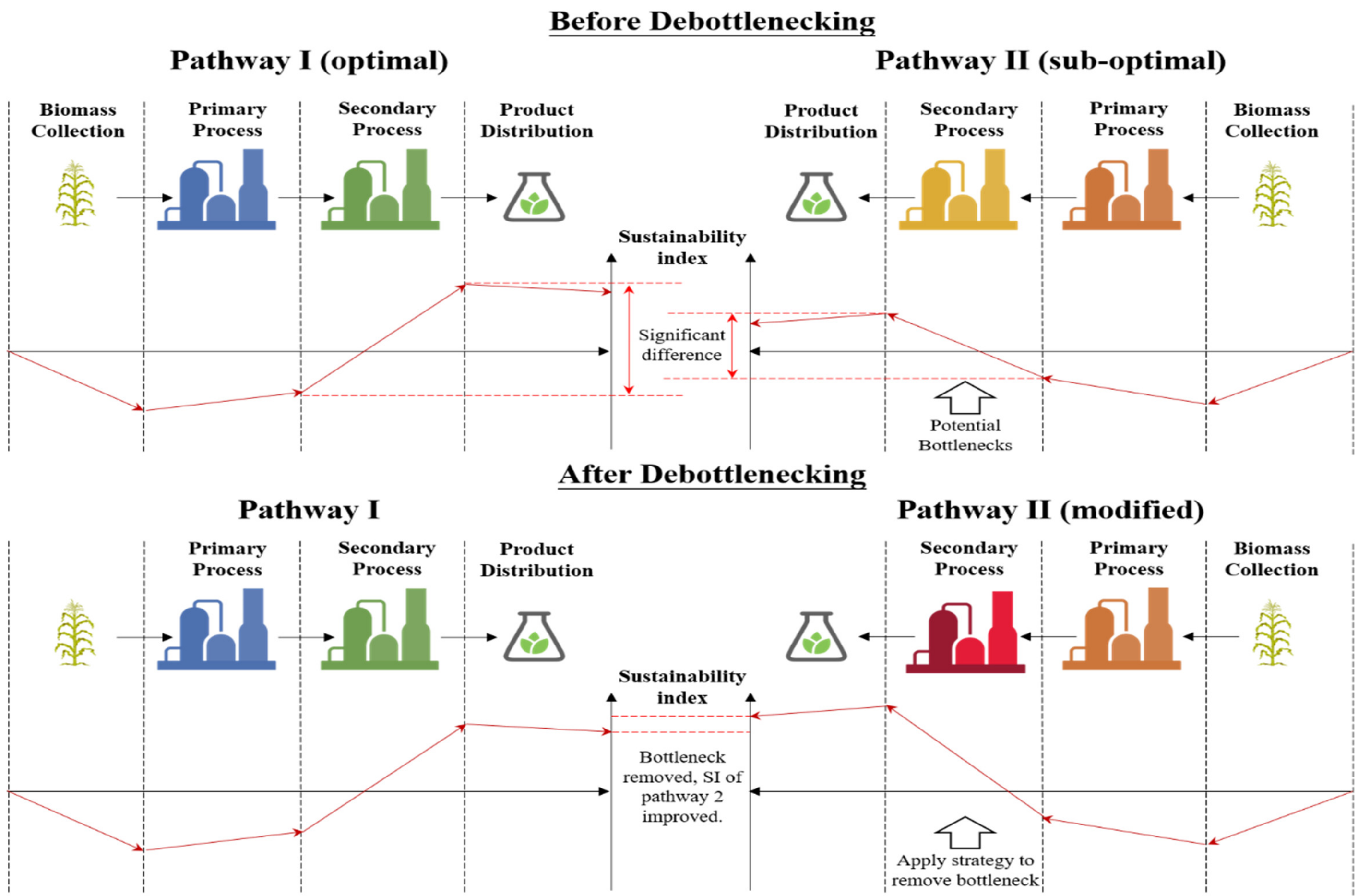

Figure 2.5: Conceptual illustration of debottlenecking at planning phase.

2.7 Summary of Research Gaps

Table 2.18 outlines some of the remaining research gaps in this research field. These research gaps are addressed in this PhD Thesis.

Table 2.18: Summary of research gaps.

Research Gap	Description
Development of integrated biomass supply chain using alternative graphical approach	There is still very limited work which deal with the multi-biomass supply chain synthesis problem. In addition, limited works have solved this research problem by using graphical optimisation approach (i.e., P-graph). With the aid of this graphical tool, decision-makers with no strong mathematical background are also able to optimise their specific model easily.
Development of transportation decisions tool with the consideration of vehicle capacity constraint	Most of previous works did not consider the vehicle capacity constraints in their optimisation model. Apart from this, there is also lacking user-friendly tool for the decision-makers to select the appropriate transportation mode.
Development of evaluation model to access the sustainability performance	Although there are various types of sustainability indicators available (refer to Section 2.4), more efforts have to be done to integrate these indexes in order to evaluate sustainability performance in BSCM effectively.
Development of debottlenecking approach	Despite there are numerous amount of research have discussed the bottlenecks of biomass industry in Malaysia (refer to Section 2.6), the development of a debottlenecking approach that able to detect and remove the sustainability bottleneck is still lacking.

Chapter 3:

Research Strategy and Methodology

3.1 Research Strategy

As stated in Chapter 1, the ultimate goal of this research is to develop a comprehensive evaluation model for a multi-biomass supply chain. However, there are gaps between researchers and industry players, which caused the research outcomes becoming under-appreciated by the decision-makers. Thus, the beauty of this research is the implementation of the following research strategies, which aims to bridge the gaps between researchers and industry players:

3.1.1 User-friendly

As not all decision-makers have a strong programming background, having a user-friendly approach, which is non-programming-knowledge dependent is very important. In fact, user-friendly (layman-liked) methods or approaches are more likely to be applied in the real-life practices compared to those which is more complex in nature. Thus, the user-friendly frameworks (e.g., P-graph) are opted and integrated to the evaluation model proposed in this research.

3.1.2 Graphical illustration

Visualised results are easier to be read and analysed by the decision-makers (reduce dimensionalities of problem). Therefore, this research also focuses on developing graphical tools which aims to help the decision-makers in extracting useful information for their case study.

3.1.3 Comprehensive and systematic

The developed approach should be comprehensive to ensure the reliability and the effectiveness of the approach. More importantly, the developed approach should be applicable and duplicable. Therefore, step-by-step systematic guidance for the proposed approach is developed to guide the decision-makers.

3.2 Research Methodology

Figure 3.1 shows that this research project has been divided into several parts based on the research scopes set in Section 1.4.

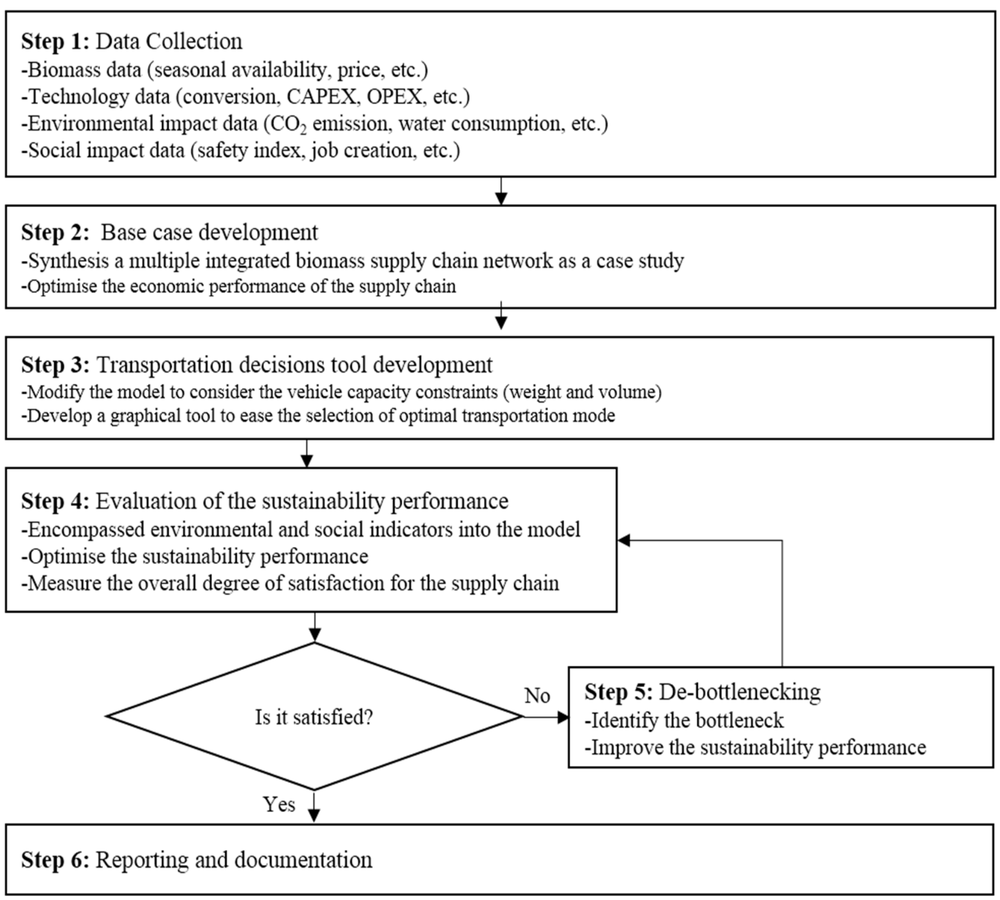

Figure 3.1: Research methodology.

The research is systematically planned and scheduled within three years. In general, the research is initiated with data collection. All data is collected from recent literatures, including industries' reports, journal papers, government official websites, etc. The data is served as inputs for the base case development (step 2 in Figure 3.1). In this step, P-graph framework is implemented as the optimisation approach due to its numerous advantageous features, including user-friendly, visualised encoding, efficient search and multiple solutions generation (see Figure 3.2). Aside from this, Site study and deep investigation of the search area are required (Phase II in Figure 3.2) to develop a mathematical model which can be solved effectively and efficiently. It divided into three steps, i.e., area fragmentation, infeasibility elimination and connectivity detachment. The detailed description of this research flowchart is given in Chapter 4.

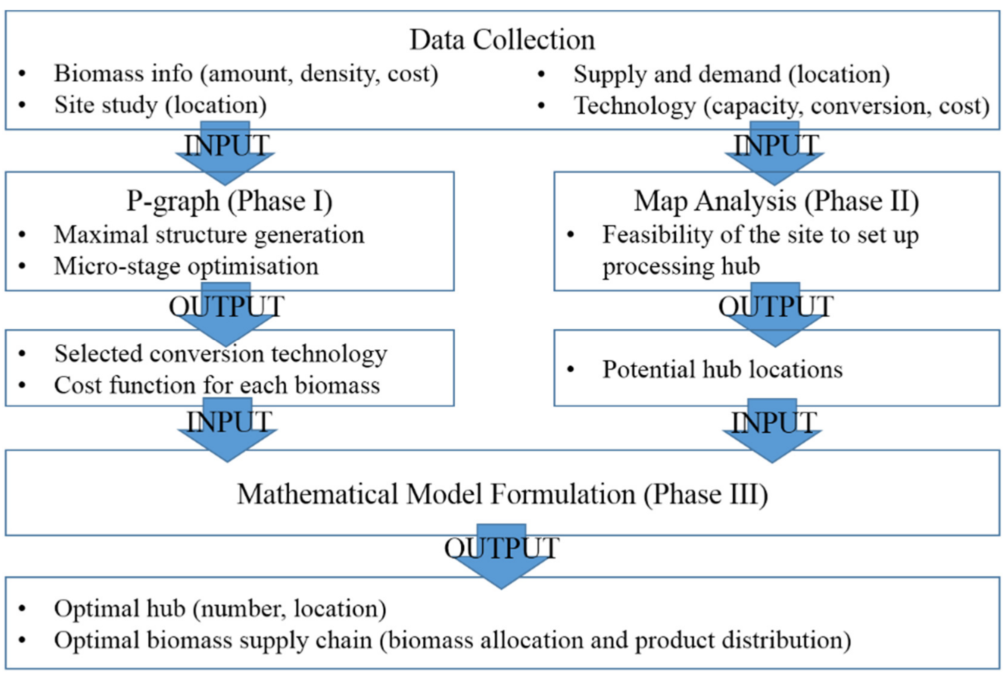

Figure 3.2: Overview of research flow chart for step 2.

Then, the base case is extended by considering vehicle capacity constraints (step 3 in Figure 3.1). Figure 3.3 shows the research flowchart proposed for this step. Note that five different transportation modes with different constraints in weight and volume limits are considered in this extended model. On top of that, a graphical decision-making tool is developed to ease the decision-makers in selecting the optimal transportation mode for their specific case study. Sensitivity analysis is also conducted to determine the effect of the assumed parameters on the obtained results. Please refer to Chapter 5 for the detailed description of this research flowchart.

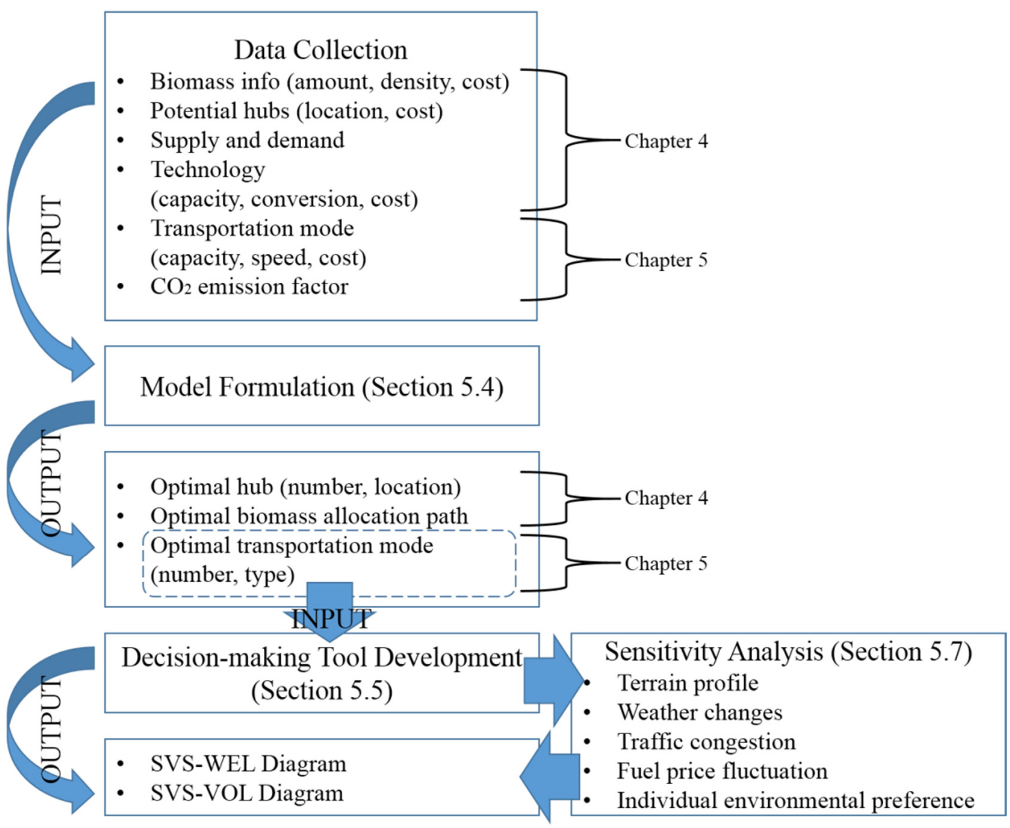

Figure 3.3: Overview of research flow chart for step 3.

Furthermore, sustainability indicators to assess environmental sustainability and social sustainability are also being integrated into the optimisation model (step 4 in Figure 3.1). Figure 3.4 presents the proposed research flowchart for this step. In order to solve this complex problem, a novel principal component analysis (PCA) aided optimisation approach is introduced. In this optimisation approach, the priority scale of each objective is determined through analytical hierarchy process (AHP). Aside from this, the obtained optimised results are compared and benchmarked with the results obtained from two other conventional optimisation approaches, i.e., weighted sum approach and max-min aggregation approach. The detailed description of this research method is presented in Chapter 6 (with environmental evaluation) and Chapter 7 (with environmental and social evaluation).

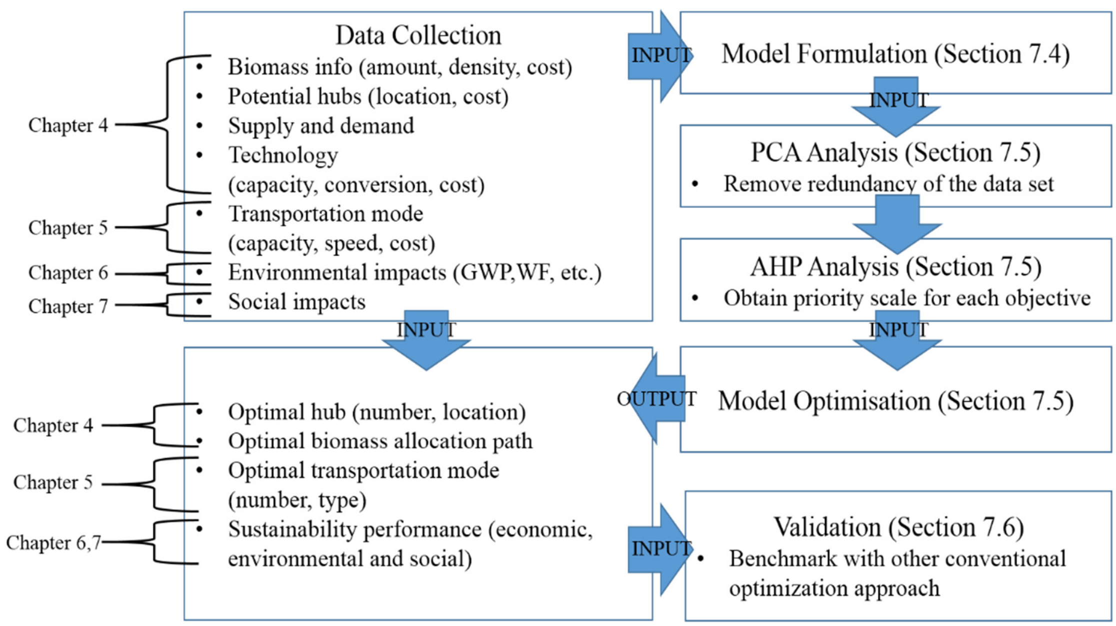

Figure 3.4: Overview of research flow chart for step 4.

Last but not least, in step 5, bottlenecks that limit the sustainability level of the supply chain is identified and subsequently removed by using the research method shown in Figure 3.5. Two individual debottlenecking approaches, one through PCA approach while another through P-graph, are developed in this step. Please refer to Chapter 8 for the step-by-step explanation for each approach. It is then followed by the documentation stage as the final step.

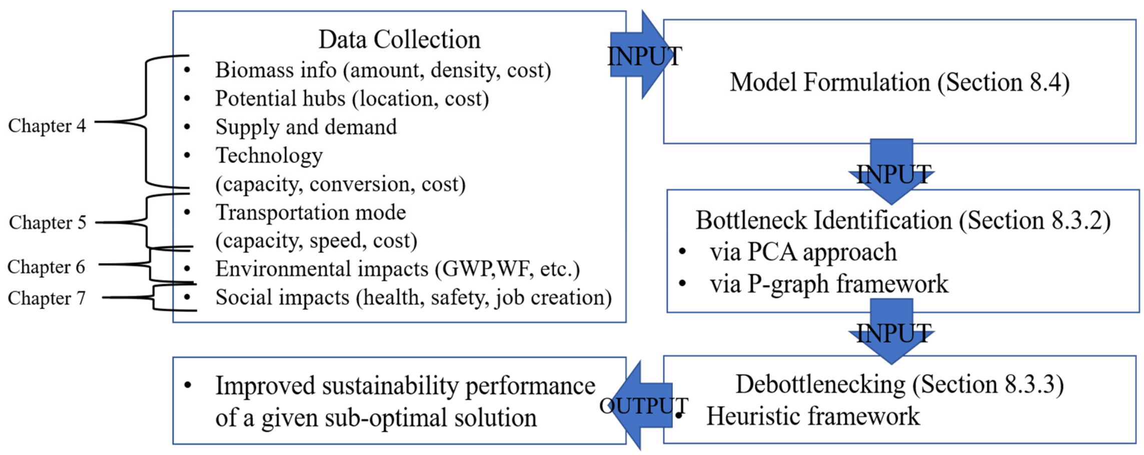

Figure 3.5: Overview of research flow chart for step 5.

Chapter 4:

P-graph Aided Two-stage Optimisation Model for Biomass Supply Chain Synthesis Problem

4.1 Introduction

As already mentioned, biomass utilisation has been cited as one of the prospective solution to achieve sustainable development in Malaysia. To-date, there are many investigations on integrating supply chain networks have been conducted. However, some of the valuable biomass in Malaysia have received relatively less attention in both research and industrial application (e.g., sugarcane bagasse, pineapple peel, etc.). Therefore, it is suggested to develop a multi-biomass supply chain, which fully utilise the potential of these biomass in order to promote the sustainability development in Malaysia. The determination of optimal structures in supply chain including transportation design, process facilities selection, processing hubs location and biomass allocation, are referred to the process network synthesis (PNS).

In this work, the notable two-stage optimisation approach which initially introduced by Lam et al. (2013) is applied. In this approach, the entire computation works are divided into two stages, i.e., (i) micro-stage optimisation (determines the optimal biomass conversion pathway) and (ii) macro-stage optimisation (determines the optimal processing hub location and biomass allocation) (see Figure 4.1). However, instead of using the conventional computational method, P-graph framework is proposed to solve the micro-stage optimisation. The main factors of incorporating P-graph framework in the two-stage optimisation model is due to its attractive computing features (e.g., simultaneous generation of optimal and sub-optimal solutions and efficient search of solution space) and its visual interface for data encoding and results display (Lam et al., 2016). By using this graphical approach, decision-makers with minimal programming background are also able to develop or analyse their own supply chain easily, as comparable as other users with strong mathematical programming background. The conceptual idea of the P-graph aided two-stage optimisation approach is shown in Figure 4.2. A real case study in Johor state is used to demonstrate the effectiveness of the proposed approach. The remaining part of this chapter is arranged as follows. The strategy and research methodology of the problem solving is presented in Section 4.2, while the model formulation is described in Section 4.3. Section 4.4 outlines the background of the case study in Johor while Section 4.5 refers to the discussion of research outcomes. Finally, concluding remarks are given in Section 4.6.

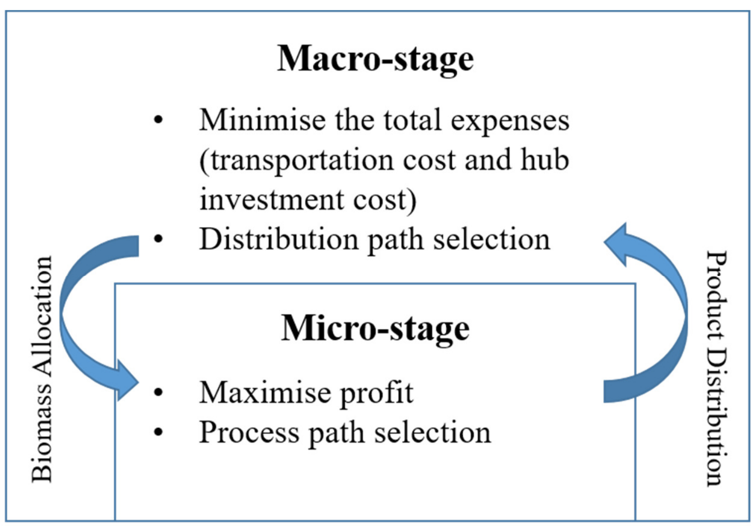

Figure 4.1: Two-stage optimisation model (Lam et al., 2013).

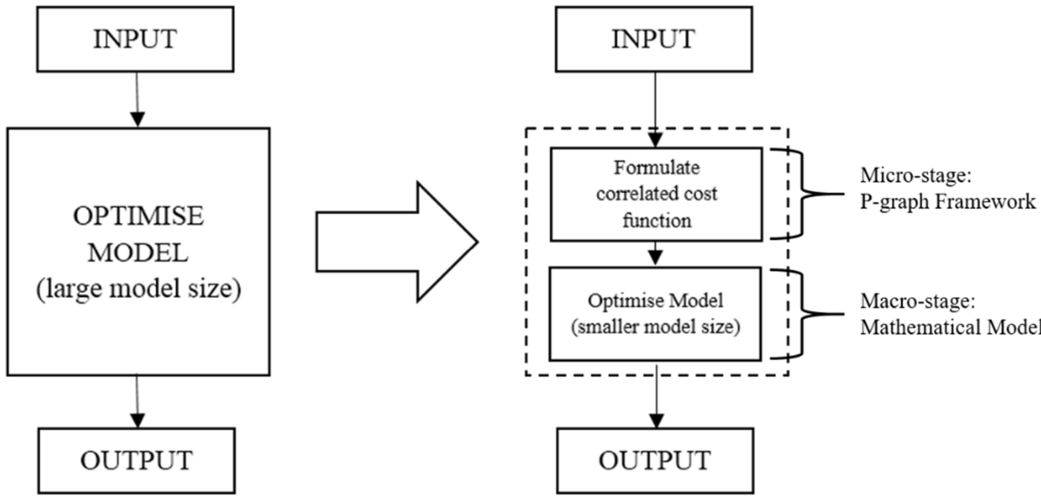

Figure 4.2: Conceptual idea of P-graph aided two-stage optimisation approach.

4.2 Methodology

The research flow chart for this work is shown in Figure 4.3. In general, the process consists of three main phases. Phase I aims to determine the correlated cost function for each biomass. This cost function is used to determine the profit that can be obtained by each biomass. It is similar to the micro-stage optimisation, which introduced by Lam et al. (2013). However, the conventional approaches, which present the selection of the operating units by integer variables, are less preferable to handle huge-size and high-complexity problems (Harvey, 2006). Without any aid of rigorous combinatorial tools, it is difficult to build the problem superstructure heuristically due to the extensive amount of operating units in these problems. Besides, if a superstructure is created heuristically, certain low-cost option would be missed out and thus, higher opportunity to miss the true optimal solution. Therefore, in order to address this issue, P-graph approach is proposed as an alternative methodology for micro-stage optimisation. Phase II aims to determine all the potential processing hub locations in a given region. In this phase, all infeasible hub locations are removed in order to reduce the model size of the mathematical model. The outcomes from Phase I and Phase II are served as the input for the mathematical model formulated in Phase III. With the aid of Lingo v14.0 (Lingo, 2015), an optimal biomass supply chain is synthesised. The description of Phases I and II are given in the subsections below, while the model formulation (Phase III) is discussed in Section 4.3.

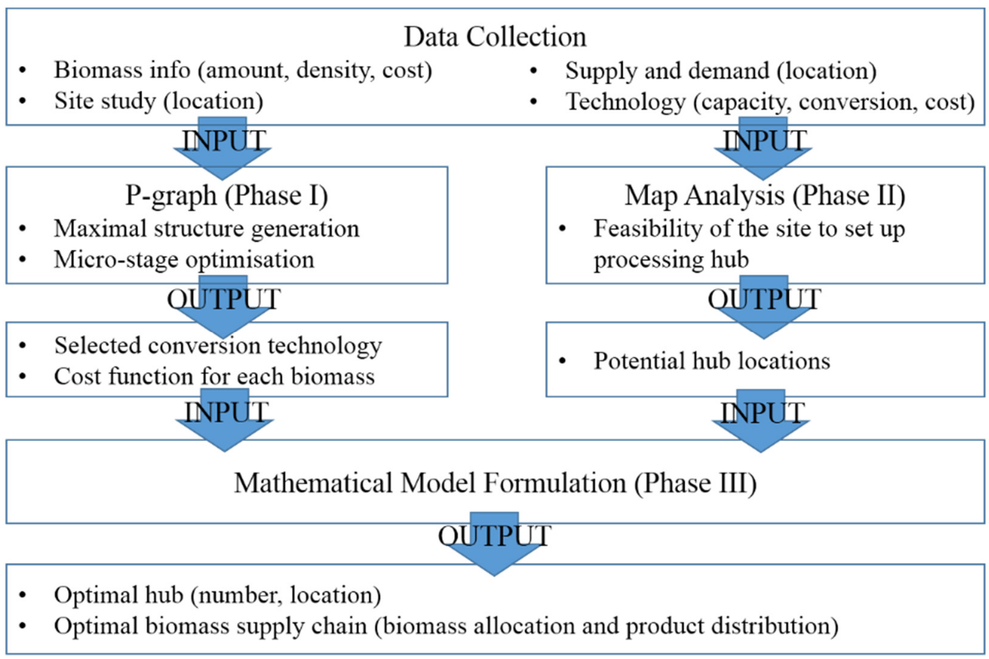

Figure 4.3: Overview of research method for Chapter 4 (reproduced from Figure 3.2).

4.2.1 Phase I

A maximal structure which refers to the union of all combinatorially feasible process structure of a synthesis problem can be constructed by using P-graph Studio, which developed by the Department of Computer Science and Systems Technology in University of Pannonia (P-Graph Studio, 2017). All the related materials, streams and operating units have to be identified in this phase. The purchasing cost of each raw materials, selling price of each product, operating and capital cost of each operating unit and conversion ratio of each process path have to be pre-defined in this phase. This is a pre-processing step for Phase II to formulate the correlated cost function. Figure 4.4 shows the graphical representation of the maximal structure of a processing hub. In the processing hub, biomass *r* is converted into various kinds of products *p*, through different technologies *t*. In some cases, biomass *r* will not be converted into products *p* directly. Instead, it will firstly be converted into intermediate *p*', then only turned into final product *p*. Note that Figure 4.4 is just an illustration, the number of technologies in between the raw material and final product does not limit to two.

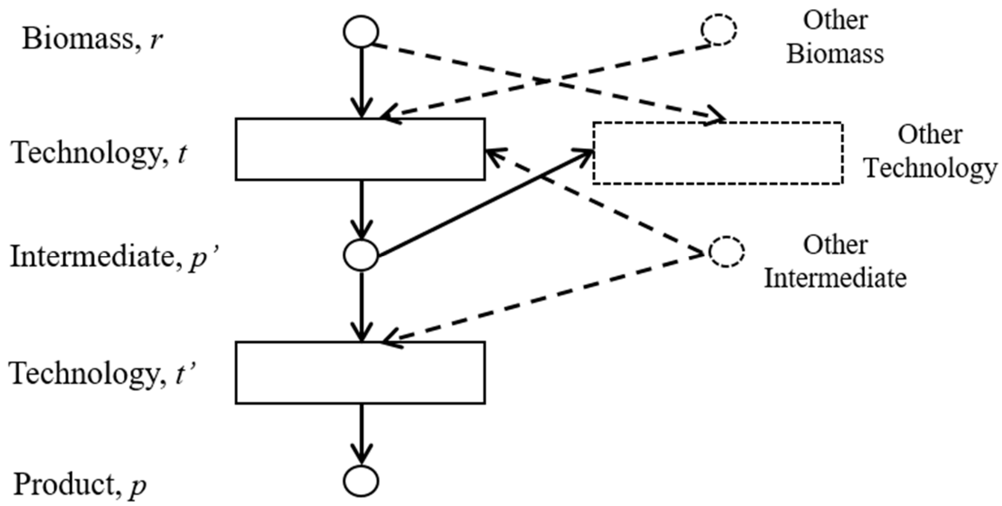

Figure 4.4: Outline of maximal structure for each processing hub.

In real life, biomass supply network usually covers a large region, leading to a complex supply chain model that consists of huge amount of "macro variables". "Macro variables" refer to the variables which used in macro-stage (determines the optimal processing hub location and biomass allocation). This includes the variables used to indicate the biomass allocation between biomass sources and processing hubs;

variables used to indicate the amount of products generated in each processing hub; variables used to indicate the distribution of products between processing hubs and demand points; binary variables used for hub determination; variables used to indicates the investment cost (i.e., transportation cost and hub investment cost).

In addition, multi-biomass supply chain normally involves a huge set of operating units and a huge set of materials (including biomass, intermediates and value-added products), causing the existence of a substantial amount of "micro variables". "Micro variables" refer to the variables used in micro-stage (determines the optimal processing hub location and biomass allocation). This includes the variables used to indicates the amount of biomass processed in each primary technology; variables used to indicate the amount of intermediates produced; variables used to indicate the amount of intermediates processed in each secondary technology; variables used to indicate the amount of products generated; and variables used to indicate the obtained gross profit.

It is worth noting that, some of the aforementioned variables are intermittent variables, which have been notified as "macro variables" and "micro variables" simultaneously (i.e., variables existed in both micro and macro stages). These intermittent variables served as a bridging component to link the micro-stage and macro-stage optimisation, and vice versa. For instance, the amount of products generated and the respective obtained gross profit which determined from micro-stage optimisation are input to the macro-stage optimisation in order to account the total obtained net profit; the amount of biomass sent to each processing hubs which determined from macro-stage is input to the micro-stage optimisation in order to determine the respective plant design. Figure 4.5 shows the generic superstructure of the research problem. Literatures have proved that this huge number of variables will reduce the model efficiency (Lam et al., 2011). Therefore, some of the model-size reduction strategies are introduced in Section 4.2.2 in order to eliminate some of the unnecessary or redundant “macro variables”.

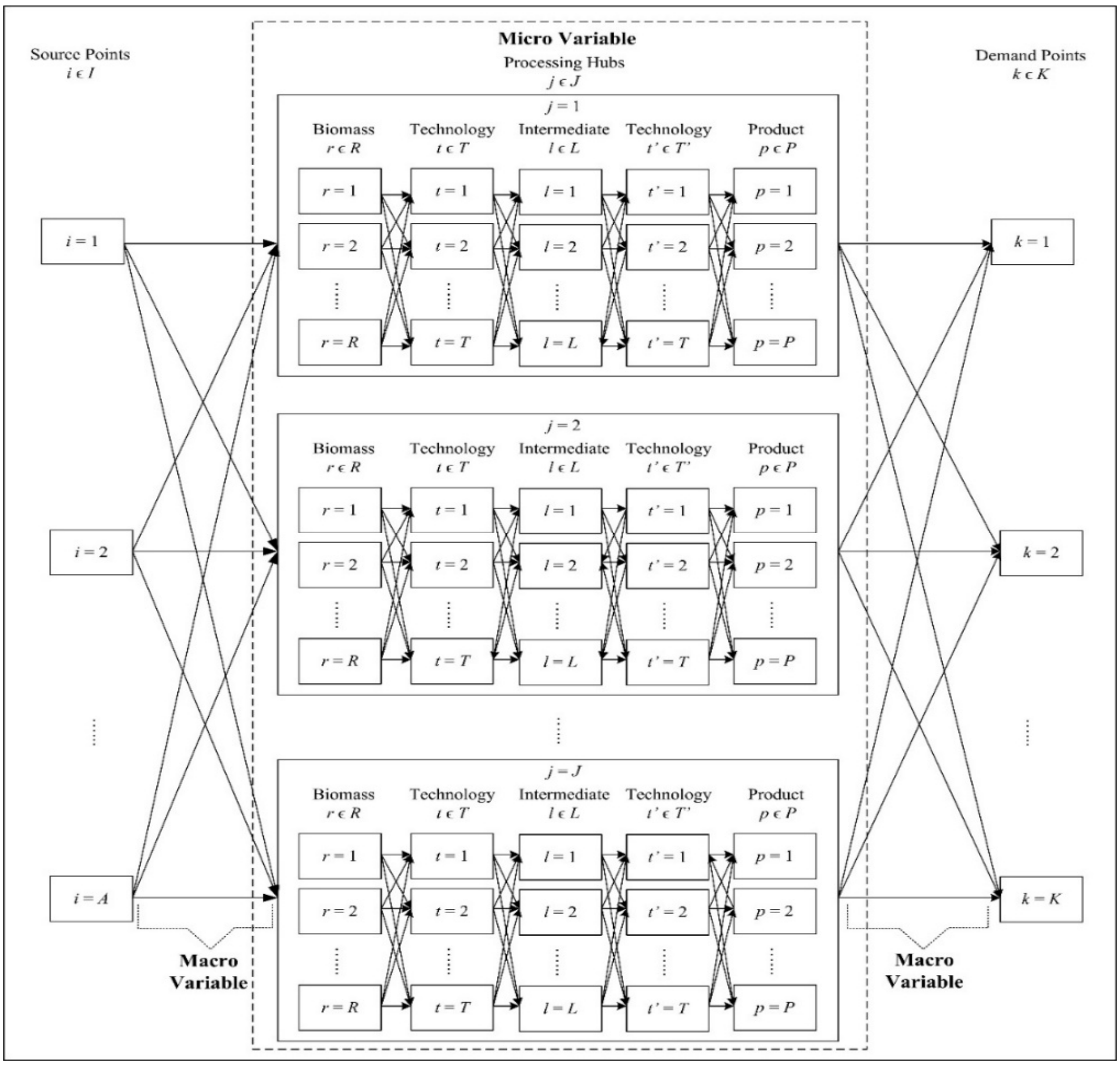

Figure 4.5: Superstructure of the multi-biomass supply chain.

In this phase, the correlation between the amounts of the raw material input and gross profit is determined. This correlated cost function can be obtained through the optimisation process done by ABB Algorithm in P-graph framework. Generally, this formulated cost function is a function of amount of raw materials input:

$$C^{\mathrm{GP}} = F_1\mathrm{C}_1 + F_2\mathrm{C}_2 + \cdots + F_r\mathrm{C}_r^{\mathrm{General}} \quad (4.1)$$

where F_1, F_2, … F_r refer to the amount of biomass, while C_1, C_2, … $\mathrm{C}_r^{\mathrm{General}}$ refer the correlated cost constant ($/ton biomass). With this cost function, the gross profit can be directly calculated by using the amount of raw materials. In other words, this will significantly reduce a great amount of "micro variables" used in the mathematical model, which is formulated in Phase III. Thus, this will improve the model efficiency significantly. For instance, if the model consists of four types biomass, four operating units, one products, and five possible hub locations, up to 80 micro variables (i.e., 4 x 4 x 1 x 5) can be eliminated from the model with the use of the formulated cost function.

However, in order to ensure reliability of the generated cost function, the P-graph model has to be constructed correctly. Figure 4.6 shows a wrong demonstration of P-graph model for biomass utilisation. In this example, biomass R can be fed into two technologies, where Technology 1 generates product P; and Technology 2 generates electricity. Note that the orange lines represent the self-generated energy while the red lines represent the imported electricity from the grid. The generated electricity can either be sold or self-consumed by Technology 1. However, this structure creates several restrictions for the model:

I. Technology 1 will only be selected when both imported and self-generated energy are existing.

II. The input ratio of imported energy and self-generated energy have to be pre-fixed in this case.

III. The output ratio of exported energy (sell) and recycled energy have to be pre-fixed in this case.

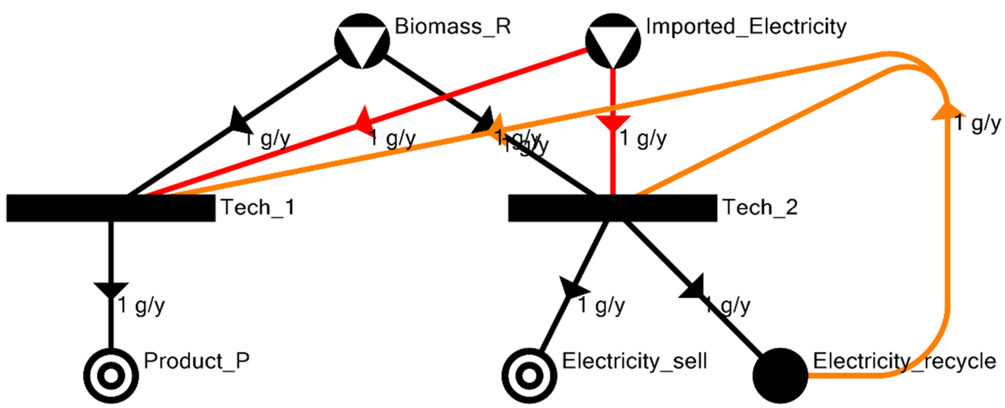

Figure 4.6: Wrong demonstration example.

These restrictions have gradually reduced the model flexibility. In order to solve this issue, “imaginary operating unit” is introduced (blue rectangular bar) (see Figure 4.7). By having this configuration, electricity input to Technology 1 and the distribution ratio of self-generated electricity (to sell or recycle) is no longer constrained. Note that the yellow lines refer to the mixture of imported and self-generated electricity.

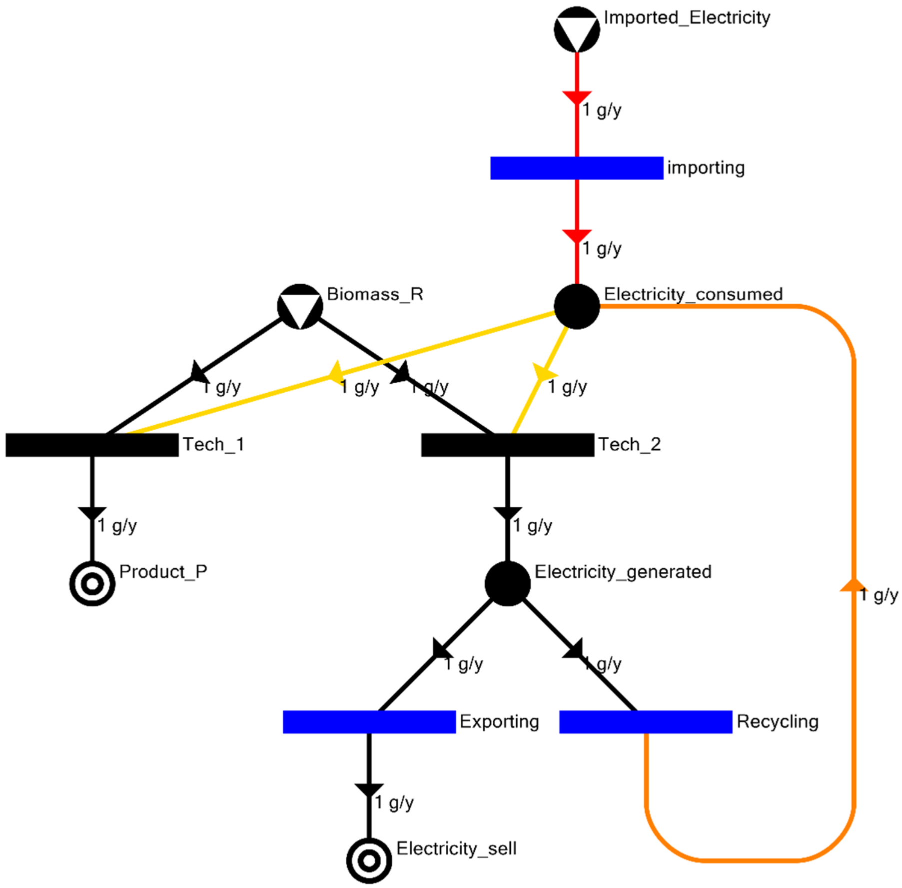

Figure 4.7: Correct demonstration example.

4.2.2 Phase II

Site study and deep investigation of the search area are required to develop a mathematical model which can be solved effectively and efficiently. It divided into three steps, i.e., area fragmentation, infeasibility elimination and connectivity detachment. All three steps are aimed to reduce the model sizes by removing unnecessary or redundant "macro variables".

4.2.2.1 Area Fragmentation

Processing hub determination is one of the key problems to be solved in multi-biomass supply chain. In order to simplify the problem, the huge study area is "fragmentised" into smaller "zones". Each zone is served as a potential location to set up the processing hub. Figure 4.8 is an illustration of this step, the entire study area (white-coloured area) has been divided into smaller areas by the grid lines. The areas embedded by the horizontal and vertical grid lines are termed as "zone". Several previous works have applied this pre-processing step before conducting their model. For instance, Lam et al. (2011) divides the study region into several supply and collection zones. Lately, Čuček et al. (2013) divides network's region into 36 zones and classify them as the potential locations for biorefineries. Fundamentally, if smaller zones (i.e., smaller area) are created (fragmentised into more zones), the obtained results will be relatively closer to the global optimal. Therefore, a Pareto analysis is conducted in Section 4.5.4 to investigate the effect of fragmentised area on the objective function.

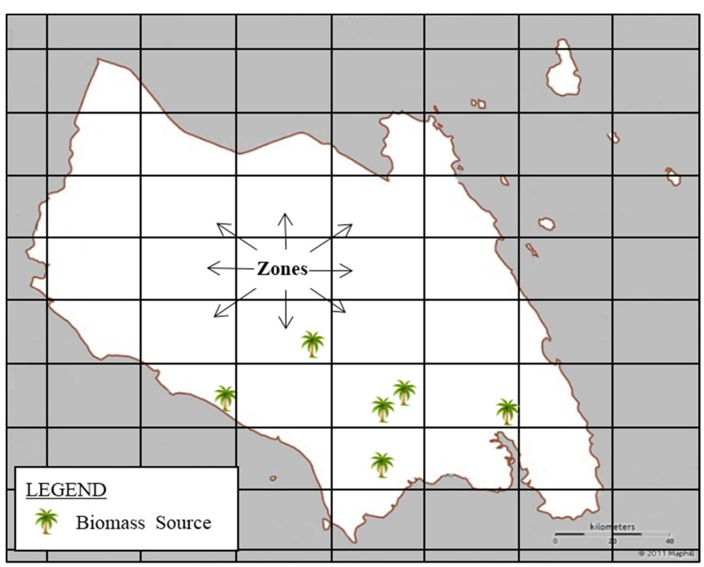

Figure 4.8: An illustration of area fragmentation (Maphill, 2013).

4.2.2.2 Infeasibility Elimination

Removal of all the “infeasible” zones which are not suitable or impossible to set up processing hubs, e.g., mountain area, residential area, etc. is vital to minimize the problem size. As a result, this will decrease the burden of the solver and minimise the overall searching time. Figure 4.9 is the illustration of this step. The shaded areas are mountain areas and protected forest areas which have to be eliminated from the searching area. The advantages of having this manual screening process is to avoid meaningless results, such as (i) locations which are not suitable to set up hub (normally related geographical condition, e.g., mountain area, sea, etc.), (ii) locations which are occupied and (iii) locations which are underdeveloped (e.g., lack of water, electricity or worker supply, underdeveloped road system, etc.).

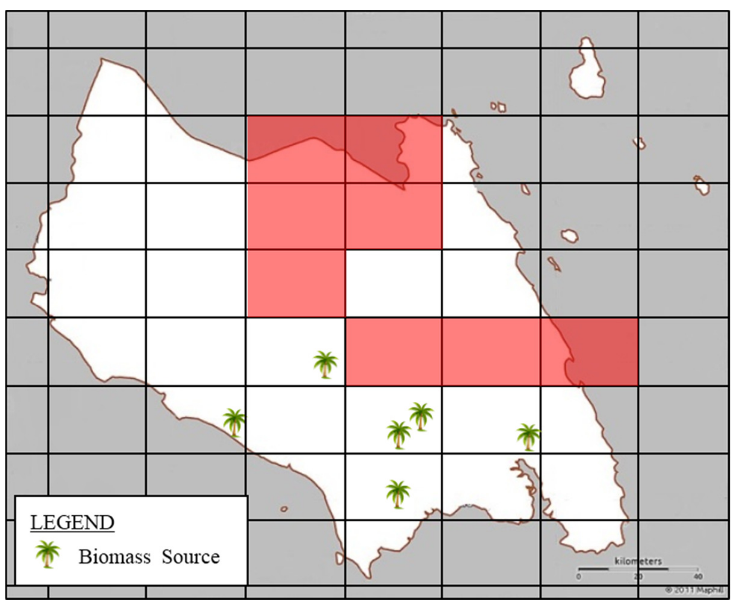

Figure 4.9: An illustration of infeasibility elimination (Maphill, 2013).

4.2.2.3 Connectivity detachment

In the original model, each starting point is connected to each possible destination (i.e., source points *i* to processing hubs *j*; and processing hubs j to customers *k*). All combinations of connectivity (cross-product multi-dimensional set IxJ and set JxK) create a complex network with a huge number of "macro variables" which will lead to a longer computation time. However, in the real scenario, there is a limitation for the traveling distance as the profit gained might not be able to compensate the transportation cost of the raw material and product. Therefore, the maximum allowable travel distance, $MATD_r$ [km] is introduced to determine the maximum travelling distance for each biomass source which is potentially economic feasible. Generally, $MATD_r$ [km] is directly proportional to the gross profit obtained per ton of biomass, C_r^{General} [$/ton biomass] of the raw material. It is defined as:

$$MATD_r = \frac{C_r^{\text{General}}}{C^{\text{T}}} \quad \forall r \in R \tag{4.2}$$

where C^{T} [RM/t biomass. km] refers to the estimated transportation cost constant, i.e., the linearlied transportation cost per unit ton of biomass, per unit km of travelled distance (in this chapter, value assumed as 0.8 [RM/t/km] (Lam et al., 2013)). Note that C_r^{General} can be determined by using Equation (4.1) (detailed gross profit calculation please refer Equation (4.12)). Figure 4.10 is an illustration of this step. Assume the two source points supply different types of biomass. Each biomass contains different C_r^{General}. The one with greater C_r^{General} can compensate higher transportation cost, thus it will have a larger search area compared to the other one. If the biomass is transferred to the zones outside from this search area, the transportation cost will be greater than the maximal gross profit that can be gained in this model. In other words, the zones located outside the search area are no longer cost-feasible and thus, the connectivity between the source point and these zones is unnecessary and should be removed prior to the next step.

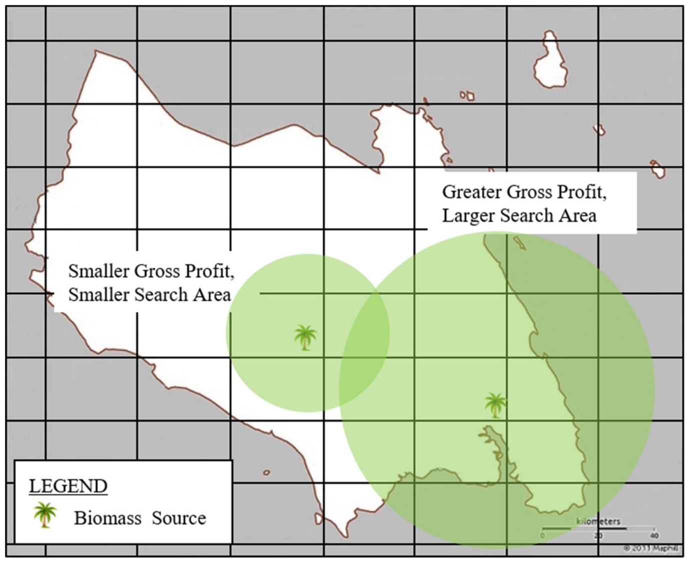

Figure 4.10: An illustration of connectivity detachment (Maphill, 2013).

4.3 Model Formulation (Phase III)

After the previous steps, the remaining zones are served as the candidate locations to set up the processing hubs. In order to determine the optimal hub location and optimal biomass allocation pathway, a mathematical model is developed. By including the correlated cost function formulated previously, the use of variables (binary and non-binary) in the model has been significantly reduced. The model formulation is defined as follow:

4.3.1 Material flow

The biomass *r* produced from each source *i,* is transported to centralized hub *j* to convert to value-added product *p* through technology *t* (and secondary technology *t'*). The intermediates are dented as *l*. All the final products *p* will be sent to the respective customer *k*. The material flows are defined as:

$$\sum_j F_{r,i,j} \leq \mathrm{F}_{r,i} \quad \forall r \in R,\ \forall i \in I \tag{4.3}$$

$$\sum_k F_{p,,j,k} \leq \mathrm{F}_{p,j} \quad \forall p \in P, \forall j \in J \tag{4.4}$$

Equations (4.3) and (4.4) are constraints that ensure the supplied amount of biomass *r* to hubs *j* and the delivered amount of product *p* to customer *k* are capped at the biomass availabilities in source *i* and the product produced in hub *j* respectively, while Equations (4.5) to (4.7) concern the material balance held within the processing hub. Note that the "zones" that are eliminated through Phase II should be manually excluded in the model formulation (see Section 4.2.2).

$$\sum_i F_{r,i,j} = \mathrm{F}_{r,j} \quad \forall r \in R,\ \forall j \in J \tag{4.5}$$

Equation (4.5) assures that the amount of biomass *r* collected in hub *j* must be equal to the total supplied amount of biomass *r* from all sources *i* to hub *j*.

$$F_{r,j} = \sum_t F_{r,t,j} \quad \forall r \in R, \forall j \in J \tag{4.6}$$

$$F_{l,j} = \sum_{t'} F_{l,t',j} \quad \forall l \in L, \forall j \in J \tag{4.7}$$

Equations (4.6) and (4.7) indicate that all biomass *r* and intermediates *l* will be further processed into desired products *p* through technology *t* (and *t'*).

$$F_{l,j} = \sum_r \sum_t (F_{r,t,j} \times X_{r,t,l}) \quad \forall l \in L, \forall j \in J \tag{4.8}$$

$$F_{p,j} = \sum_l \sum_{t'} (F_{l,t',j} \times X_{l,t',p}) \quad \forall p \in P, \forall j \in J \tag{4.9}$$

Equations (4.8) and (4.9) are the conversion functions where $X_{r,t,l}$ refers to the conversion factor of biomass *r* to intermediate *l* via technology *t*, while $X_{l,t',p}$ refers to the conversion factor of intermediate *l* to product *p* via technology *t'*.

4.3.2 Hub determination

Constraint (4.10) determine the selection of possible centralized hub *j*. $\sum_r F_{r,j}$ [t/d] is the total amount of biomass transferred to hub *j*. Note that B_j is the binary variable to denote the selection of hub *j* while M refers to the maximum hub's capacity. By using this constraint, the binary variable B_j will be forced to be "1" when $\sum_r F_{r,j}$ [t/d] is non-zero flow. It is worth to note that when there is zero flow in $\sum_\mathrm{i} F_{i,j,r}$ [t/d], B_j can be either "0" or "1" to satisfy the constraints. However, this will not be an issue as the objective function of this model is to minimise expenses, in other words, maximise the profit. Thus, B_j will be forced to be "0" in order to reduce the investment cost.

$$\sum_r F_{r,j} \leq \mathrm{M} \times B_j \quad \forall j \in J \tag{4.10}$$

The total number of hubs, num^{Hub} can be defined in Equation (4.11), note that sensitivity analysis is carried out to determine the optimum number of hubs.

$$\sum_j B_j = num^{\mathrm{Hub}} \tag{4.11}$$

4.3.3 Economic evaluation

Economic evaluation concerns on gross profit, C^{GP} [RM/y], annual transportation cost, C^{Tr} [RM/y] and annualised hub investment cost, $C^{\mathrm{Inv\_Hub}}$ [RM/y].

4.3.3.1 Gross Profit

C^{GP} is determined by revenue obtained from final products p ($\mathrm{C}_p^{\mathrm{Product}}$ [RM/t]) subtract the collection cost of biomass r ($\mathrm{C}_r^{\mathrm{Biomass}}$ [RM/t]), annual operating cost ($\mathrm{C}_t^{\mathrm{OPEX\_Tech}}$ [RM/t] and $\mathrm{C}_{t'}^{\mathrm{OPEX\_Tech}}$ [RM/t]) and annualised capital cost ($\mathrm{C}_t^{\mathrm{CAPEX\_Tech}}$ [RM/t] and $\mathrm{C}_{t'}^{\mathrm{CAPEX\_Tech}}$ [RM/t]). It is written as:

$$C^{\mathrm{GP}} = \Big\{\sum_p\Big(\sum_j F_{p,j} \times \mathrm{C}_p^{\mathrm{Prod}}\Big) - \sum_r\Big(\sum_i F_{r,i} \times \mathrm{C}_r^{\mathrm{Biomass}}\Big) - \sum_t\Big(\sum_r \sum_j F_{r,t,j} \times \mathrm{C}_t^{\mathrm{OPEX\_Tech}}\Big) - \sum_{t'}\Big(\sum_l \sum_j F_{l,t',j} \times \mathrm{C}_{t'}^{\mathrm{OPEX\_Tech}}\Big) - \sum_t\Big(\sum_r \sum_j F_{r,t,j} \times \mathrm{C}_t^{\mathrm{CAPEX\_Tech}}\Big) - \sum_{t'}\Big(\sum_l \sum_j F_{l,t',j} \times \mathrm{C}_{t'}^{\mathrm{CAPEX\_Tech}}\Big)\Big\} \times \mathrm{OPD} \tag{4.12}$$

where OPD [d/y] refers to the estimated total working days per year. It is worthy to note that $\mathrm{C}_t^{\mathrm{OPEX\_Tech}}$ [RM/t] and $\mathrm{C}_{t'}^{\mathrm{OPEX\_Tech}}$ [RM/t] cover all the operating expenditures, including utility cost, workers' salary, maintenance cost, etc.; while $\mathrm{C}_t^{\mathrm{CAPEX\_Tech}}$ [RM/t] and $\mathrm{C}_{t'}^{\mathrm{CAPEX\_Tech}}$ [RM/t] cover all the one-time expenses, including machinery cost, legal permit cost, etc.

In order to simplify the model complexity, the correlated cost constant ($\mathrm{C}_r^{\mathrm{General}}$ [RM/t]) which is formulated in Equation (4.1) is implemented into the model. By using this cost function, C^{GP} [RM/y] can be determined easily from the model, without including a massive number of variables into the model. As a result, Equation (4.12) is revised as:

$$C^{\mathrm{GP}} = \sum_r (\sum_j F_{r,j} \times \mathrm{C}_r^{\mathrm{General}}) \times \mathrm{OPD} \qquad (4.13)$$

4.3.3.2 Annual transportation cost

C^{Tr} can be determined by using Equation (4.14):

$$C^{\mathrm{Tr}} = (\sum_i \sum_j (\sum_r F_{r,i,j} \times \mathrm{d}_{i,j}) + \sum_j \sum_k (\sum_p F_{p,j,k} \times \mathrm{d}_{j,k})) \times \mathrm{C}^{\mathrm{T}} \times \mathrm{OPD} \qquad (4.14)$$

where $\mathrm{d}_{i,j}$ and $\mathrm{d}_{j,k}$ refer to the distance travelled between source *i* and hub *j* and distance travelled between hub *j* to demand *k*. It is worth noting that the distance used is actual distance extracted from Google Map instead of using displacement between the two locations. In this Chapter, the transportation cost is determined based on an linearised transportation cost constant, C^{T} [RM/t/km] (value is assumed as 0.8). The more accurate transportation cost calculation, which considers physical capacity constraints of the vehicle, delivery lead time, etc. is discussed in Chapter 5.

4.3.3.3 Annualised hub investment

$C^{\mathrm{Inv\_Hub}}$ is referring to the fixed cost required to set up a processing hub, which includes land cost ($\mathrm{C}^{\mathrm{Land}}$ [RM]) and construction expenses ($\mathrm{C}^{\mathrm{Construct}}$ [RM]). It is annualised by using capital recovery factor (CRF) which converts a present value to a stream of equal annual cost over a life span ($\mathrm{LS}^{\mathrm{Hub}}$ [y]) at a specified discount rate ($\mathrm{rate}^{\mathrm{int}}$ [%]). They are defined as:

$$C^{\mathrm{Inv\_Hub}} = num^{\mathrm{Hub}} \times \left(\mathrm{C}^{\mathrm{Land}} + \mathrm{C}^{\mathrm{Construct}}\right) \times \mathrm{CRF} \tag{4.15}$$

$$\mathrm{CRF} = \frac{\mathrm{rate}^{\mathrm{int}}(1+\mathrm{rate}^{\mathrm{int}})^{\mathrm{LS}^{\mathrm{Hub}}}}{(1+\mathrm{rate}^{\mathrm{int}})^{\mathrm{LS}^{\mathrm{Hub}}}-1} \tag{4.16}$$

4.3.4 Objective function

The model is structured to minimise the net profit, C^{NP}, note that this multi-biomass supply chain is modelled through mixed integers linear programming (MILP). It is solved by using Lingo v14.0 (Lingo, 2015) with global solver.

$$\max C^{\mathrm{NP}} = C^{\mathrm{GP}} - C^{\mathrm{Inv\_Hub}} - C^{\mathrm{Tr}} \tag{4.17}$$

4.4 Case Study Description

A case study is used to demonstrate the effectiveness of the proposed method. The descriptions of the selected case study are given in the following sub-sections:

4.4.1 Biomass availability

Johor, a southern state of Malaysia, which is prosperous in its natural resources in the fields of agriculture is selected as the study area. In this case study, palm oil biomass, paddy biomass, sugarcane bagasse and pineapple peels are chosen as the biomass sources due to its abundant availability and substantial economic potential. In this work, 6 major palm oil mills, 5 paddy fields, 8 sugarcane plantation areas and 6 pineapple plantation areas are considered. The amount of each biomass available in each source point is tabulated in Table 4.1. Figure 4.11 shows the geographical location of each source in Johor map.

Table 4.1: Biomass availability in Johor (MPOB, 2012; DOA, 2012; DOA, 2013; DOA, 2014).

Source	Longitude	Latitude	Supply [t/y]	Source	Longitude	Latitude	Supply [t/y]
i_1	102.6248	2.3512	1,552	i_{14}	103.4639	1.5215	155
i_2	103.8532	2.4132	5.6	i_{15}	103.3677	2.0260	1,174,275
i_3	102.5928	2.0418	3,555	i_{16}	103.5522	1.6667	939,420
i_4	103.3616	2.0255	53.2	i_{17}	103.9340	1.7826	352,282
i_5	103.6130	1.5234	549	i_{18}	102.8375	1.9916	1,051,475
i_6	102.7988	2.5350	269	i_{19}	103.3789	1.9057	469,710
i_7	103.5511	1.6667	244	i_{20}	103.6666	1.6074	704,565
i_8	103.9339	1.7826	100	i_{21}	102.6260	2.3532	2,769
i_9	102.6247	2.3542	555	i_{22}	103.8532	2.4132	2,662
i_{10}	102.5902	2.0412	664	i_{23}	102.5928	2.0420	1,601
i_{11}	103.3622	2.0255	316	i_{24}	103.3616	2.0202	377
i_{12}	102.7940	2.5353	1,537	i_{25}	102.8370	1.9889	352
i_{13}	103.9335	1.7806	171				

Biomass types: i_1-i_8 (Sugarcane bagasse); i_9-i_{14} (Pineapple peel); i_{15}-i_{20} (Palm oil biomass); i_{20}-i_{25} (Paddy biomass);

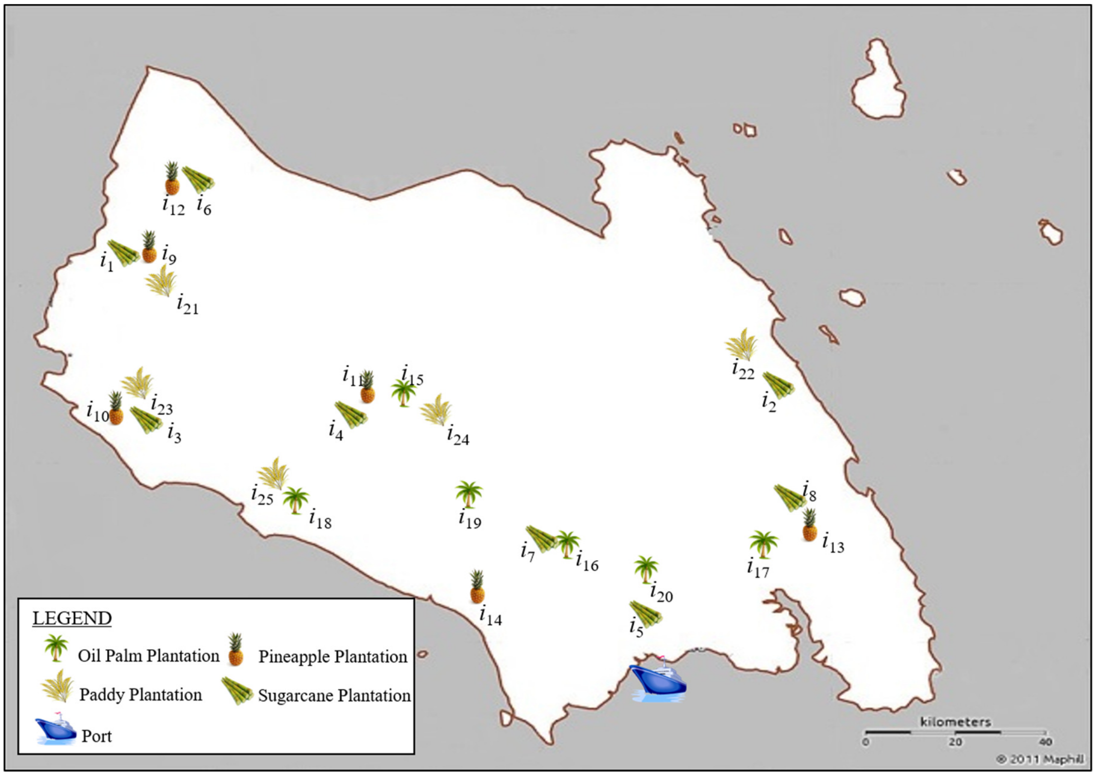

Figure 4.11: Geographical location of biomass source and port (Maphill, 2013).

4.4.2 Conversion technologies in processing hub

Generally, EFB will undergo four different processes, i.e., grinding, drying, sieving and bailing in order to yield dried long fibre (DLF); while PKS can be converted into briquette. However, the economic potential of briquette is not attractive. Thus, it will be further processed into Energy Pack which contains higher heating value by injecting it with excess industrial waste (Ng et al., 2014). On the other hand, rice husk which contains high energy content can be further converted into bio-char, syngas and py-oil via pyrolysis (Tsai et al., 2007). Both fast and slow pyrolysis are considered in this case study. Moreover, sugarcane bagasse has to be pre-treated before converting into bio-ethanol via fermentation. The literature review of the available pre-treatment methods is mentioned in Chapter 2 (please refer to Section 2.3). In this case study, four pre-treatment processes are considered, i.e., dilute acid pre-treatment, dilute alkaline pre-treatment, hot water pre-treatment and stem explosion pre-treatment. It is worth to note that, each will yield different amount of bio-ethanol and will affect the overall operating cost and capital cost. Furthermore, pineapple peels can be either converted into citric acid via solid-state fermentation (Chau & David, 1995) or further conditioned as animal feed. It can even undergo anaerobic digestion to produce methane gas which can be burnt to produce electricity via steam engine. Last but not least, EFB, PKS, paddy straw and bagasse can be used as the boiler fuel to generate high pressure steam (HPS). HPS will then be sent to steam turbine to generate electricity. Figure 4.12 summaries superstructure of process flow of each biomass. The conversion factor and the electricity requirement for each technology is tabulated in Table 4.2 and Table 4.3.

Table 4.2: Conversion ratio for each conversion pathway.

Biomass	Technology	Conversion	Reference
Palm Oil	Gasification	299[a] L Bio-oil/t EFB	(Pradana & Budiman, 2015)
		0.20 t Bio-char/t EFB	
		427[b] m^3 syngas/t EFB	
	DLF Production	0.3752 t DLF/t EFB	(EC, 2014)
	Briquetting	0.33 t Briquette/t PKS	
	Boiler	2.59 t HPS/t EFB	
		3.96 t HPS/t PKS	
Paddy	Fast Pyrolysis	500[a] L Bio-oil/t Rice Husk	(Brownsort, 2009)
		0.15 t Bio-char/t Rice Husk	
		208[b] m^3 syngas/t Rice Husk	

Table 4.2 (cont'): Conversion ratio for each conversion pathway.

Biomass	Technology	Conversion	Reference
Paddy	Slow Pyrolysis	299[a] L Bio-oil/t Rice Husk	(Brownsort, 2009)
		0.35 t Bio-char/t Rice Husk	
		315[b] m^3 syngas/t Rice Husk	
	Conditioning	0.7 t fertiliser/ t Paddy Straw	(Liao et al., 2013)
	Boiler	4.79 t HPS/t Paddy Straw	-
Sugar Cane	Bio-ethanol Production (Fermentation)	252.6[c] L/t Bagasse	(Kumar & Murthy, 2011)
		255.8[d] L/t Bagasse	
		255.3[e] L/t Bagasse	
		230.2[f] L/t Bagasse	
	Boiler	2.2 t HPS/t Bagasse	(Munir et al., 2004)
Pineapple	Anaerobic Digestion	55 m^3 Biogas/t Pineapple Waste	(Chulalaksananukul et al., 2012)
	Biogas-to-Power Generation	6 kWh/m^3 Biogas	(Energypedia, 2010)
	Drying	0.60 t Dried Pineapple/t Pineapple Waste	-
	Solid Fermentation	0.194 t Citric Acid/t Pineapple Waste	(Belén et al., 2010)
All	Turbine	0.58 kW/(t/h) HPS	(EC, 2014)

[a] Assume density of bio-oil is 1170 g/L (Gansekoele, 2016).
[b] Assume density of syngas is 0.95 g/L (Brar et al., 2013).
[c] Yield from dilute-acid pre-treatment. [d] Yield from dilute-alkaline pre-treatment.
[e] Yield from hot water pre-treatment. [f] Yield from steam explosion pre-treatment.

Table 4.3: Electricity consumption rate for each activity.

SCM Activities	Electricity Requirement [kW/(t/h) biomass]	Reference
DLF production	220	(EC, 2014)
Energy pack production	140	(EC, 2014)
Gasification	280	(NCPC, 2014)
Fast Pyrolysis	180	(NCPC, 2014)
Slow pyrolysis	150	-
Bio-ethanol Production (Fermentation)	58.19[a]	(Kumar & Murthy, 2011)
	62.46[b]	
	57.48[c]	
	36.14[d]	
Drying	30	-
Citric Acid Production	81.25	(Vogelbusch, 2015)
Biogas-energy generation[f]	35	(Nayono, 2009)
Transportation [g/L fuel]	0.00	-
Importing external energy [m^3/kWh]	0.00	(Pikoń, 2012)
Combustion [m^3/kWh]	0.00	(Pikoń, 2012)

[a] Undergo dilute acid pre-treatment. [b] Undergo dilute alkaline pre-treatment.
[c] Undergo hot water pre-treatment. [d] Undergo steam explosion pre-treatment.

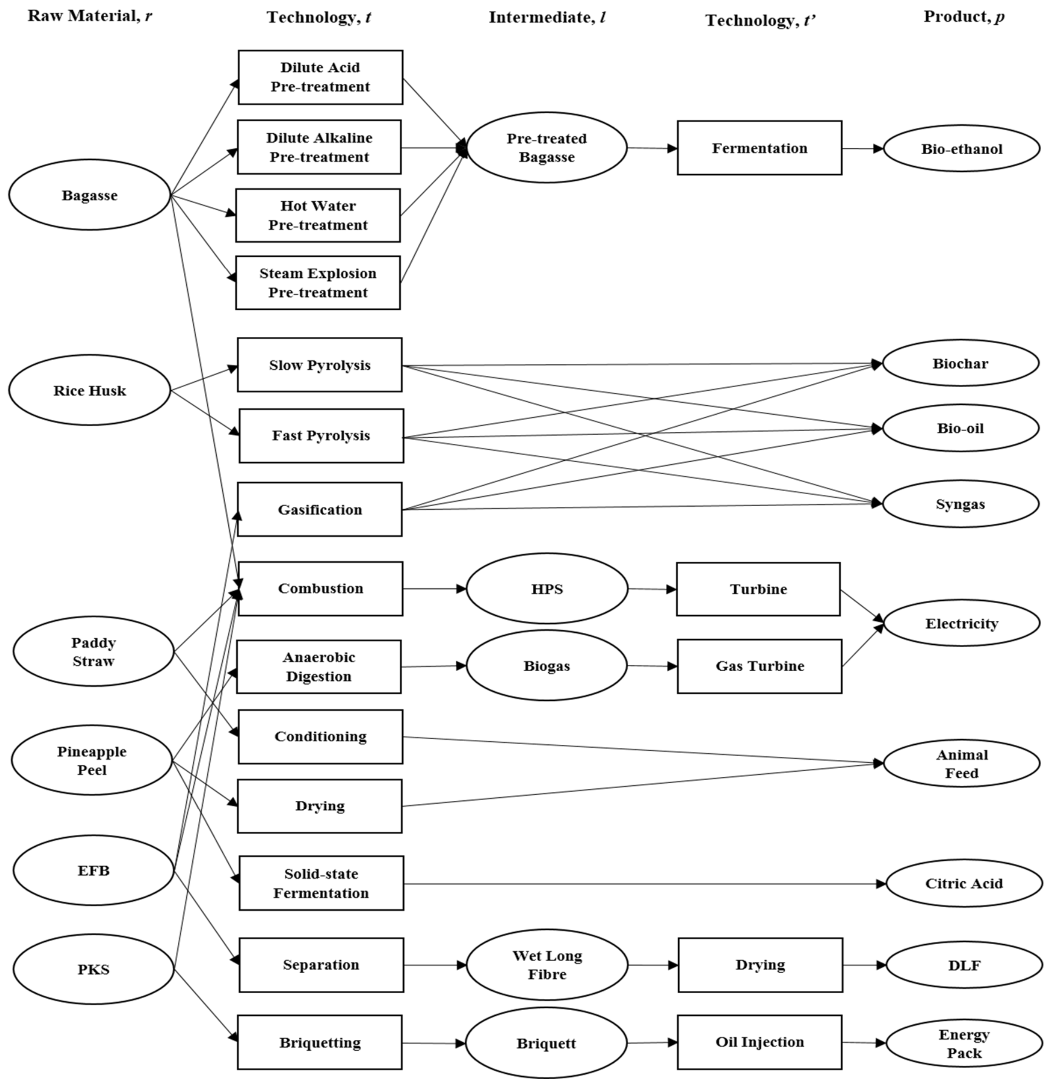

Figure 4.12: Superstructure of the process flow of each biomass.

4.4.3 Potential processing hubs

The processing hubs should be set up in the strategic location where the distance between the sources and the hubs are adequate. This is to reduce the transportation cost of the biomass. Note that the power supply and the labour supply in these regions are sufficient and the road system is well developed. The potential locations to set up the processing hubs will be discussed in the Section 4.5.2.

4.4.4 Economic data

In order to determine the overall economic potential of the synthesised biomass supply chain, several costs have to be considered. The material cost of biomass feedstock, product and utility are listed in Table 4.4 while CAPEX and OPEX for each technology are tabulated in Table 4.5.

Table 4.4: Material cost for biomass feedstock, product and utility.

Item	C_p^{Prod} [RM]	Reference	Item	$C_r^{Biomass}$ [RM]	Reference
Bio-char	1,260/t	(Kulyk, 2012)	EFB	10.8/t	(Lam et al., 2013)
Bio-oil	1.1/L	(EUBIA, 2012)	PKS	12.6/t	(Lam et al., 2013)
Bio-ethanol	3.04/L	(Macrelli et al., 2012)	Sugarcane Bagasse	10/t	-
Animal Feed	260/t	-	Paddy Straw	58.5/t	(Drake, 2006)
Citric Acid	2,520/t	-	Rice Husk	90/t	(Bhattacharyya, 2014)
Syngas	0.60/m^3	(Syntes, 2016)	Pineapple waste	10/t	-
Electricity (Export)	0.43/kWh	(Lam et al., 2013)			
Electricity (Import)	0.55/kWh	(Lam et al., 2013)			
DLF	720/t	(Lam et al., 2013)			
Energy Pack	600/t	(Lam et al., 2013)			

Table 4.5: CAPEX and OPEX for each technology.

Item	$C_t^{CAPEX\_Tech}$ [RM]	$C_t^{OPEX\_Tech}$ [RM]	Reference
DLF Production	32.4/(t/h)	66.6/(t/h)	(EC, 2014)
Gasification	150/(t/h)	180/(t/h)	-
Energy Pack Production	27.3/(t/h)	66.3/(t/h)	(EC, 2014)
Bio-ethanol Production (Fermentation)	175/(t/h)[a]	270/(t/h)[a]	(Kumar & Murthy, 2011)
	159/(t/h)[b]	260/(t/h)[b]	
	158/(t/h)[c]	255.6/(t/h)[c]	
	142/(t/h)[d]	230/(t/h)[d]	
Drying	30/(t/h)	30/(t/h)	-
Citric Acid Production	120/(t/h)	200/(t/h)	-
Anaerobic Digestion	173/(t/h)	202/(t/h)	(Weersink & Mallon, 2007)
Slow Pyrolysis	173/(t/h)	108/(t/h)	(Lehmann & Joseph, 2015)
Fast Pyrolysis	141/(t/h)	171/(t/h)	(Wright et al., 2010)
Boiler	9.4/(t HPS/h)	-	(EC, 2014)
Turbine	0.18/kW	0.18/kW	(EC, 2014)

[a] Yield from dilute-acid pre-treatment. [b] Yield from dilute-alkaline pre-treatment.
[c] Yield from hot water pre-treatment. [d] Yield from steam explosion pre-treatment.

4.5 Result and Discussion

The P-graph aided two-stage optimisation model is applied to solve the aforementioned case study. The results in each stage is shown and discussed in the following sub-sections:

4.5.1 Phase I

In this phase, the biomass conversion process in Figure 4.12 is converted into P-graph model. Figure 4.13 presents the maximal structure of the proposed case study. It is then optimised by using the ABB algorithm in P-graph Studio (P-Graph Studio, 2017). The formulated cost function for this case study is stated in Equation (4.18). Note that r_1, r_2, r_3, r_4 represent the amount of harvested sugarcane, pineapple, oil pam and paddy in tonnes respectively.

$$f(r_1, r_2, r_3, r_4) = 89.85r_1 + 22.84r_2 + 61.19r_3 + 124.34r_4 \quad (4.18)$$

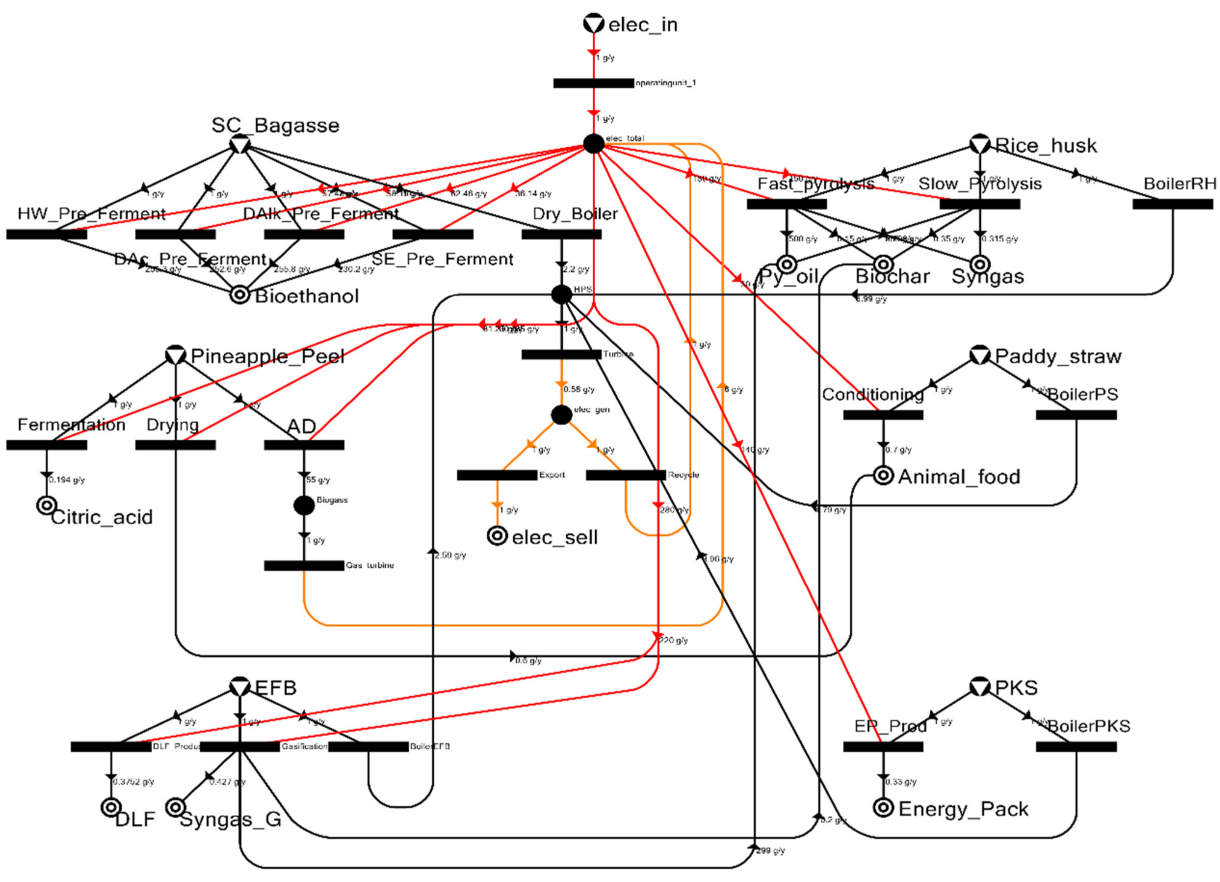

Figure 4.13: MSG of biomass utilisation process.

Note that the constant in the cost function reflect the economic potential of the biomass while the constants in the boundaries function indicate the weight ratio of each biomass utilised in the hub. In general, EFB is utilised as the gasification feedstock in order to produce valuable bio-oil; PKS is converted into energy pack, which contain high energy value; paddy straw and pineapple peel is further conditioned into animal feed; rice husk is processed through slow pyrolysis in order to maximise the bio-char and syngas yields. The results for the technology selection is summarised in Figure 4.14 (please refer to Appendix Section A.1.1 for the P-graph illustration).

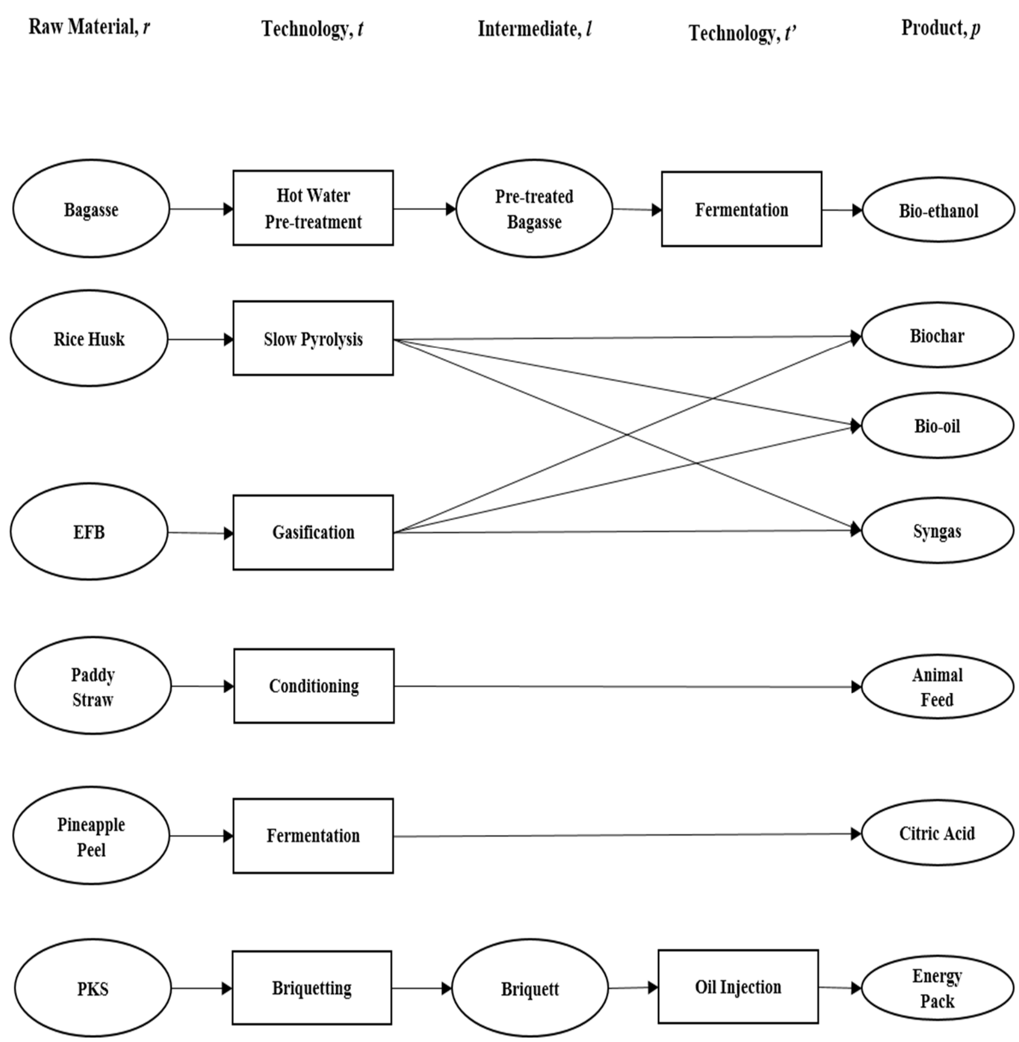

Figure 4.14: Technology selection through P-graph.

4.5.2 Phase II

In Phase II, the studied area has been divided into 33 zones via Area Fragmentation (600 km^2 per zone). During "feasibility elimination", 8 zones which located in mountain area are eliminated. After "connectivity detachment" one more zone which located north-east of Johor is removed (located too far from each source). The superimposed feasible processing hub locations are then presented in Figure 4.15. Table 4.6 summarised all the 25 potential hubs location and the respective geographical location is shown in Figure 4.16. Based on the data stated in Table 4.6, the distance between each location are determined through Google Map (see Table 4.7).

Table 4.6: Locations of potential hubs.

Hub	Longitude	Latitude	Hub	Longitude	Latitude
j_1	102.5274	2.6638	j_{14}	103.6560	2.4036
j_2	102.6691	2.4163	j_{15}	103.2903	1.8664
j_3	102.8303	2.6361	j_{16}	103.3789	1.9057
j_4	102.8340	2.4981	j_{17}	103.5734	1.6703
j_5	103.8509	2.4092	j_{18}	103.4639	1.5215
j_6	103.8627	2.4057	j_{19}	103.5184	1.5324
j_7	102.6979	2.4184	j_{20}	103.6766	1.6033
j_8	102.6644	2.2178	j_{21}	103.9162	1.4800
j_9	102.6247	2.3512	j_{22}	103.3616	2.0259
j_{10}	103.5933	2.0418	j_{23}	104.2338	1.5578
j_{11}	102.9009	1.9731	j_{24}	103.9206	1.7555
j_{12}	102.8375	1.9916	j_{25}	103.8939	1.7483
j_{13}	103.1901	1.9378			

Table 4.7: Distance data [km].

	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}
j_1	58.5	227	85	141	204	30.3	181	233	58.5	85
j_2	31.8	229	57.7	139	199	21.2	235	228	31.8	57.7
j_3	72.3	200	98.3	136	196	21.9	173	225	72.3	98.3
j_4	60.5	213	91.5	123	183	9	160	212	60.5	91.5
j_5	199	1	193	86.1	129	211	132	90.3	199	193
j_6	202	5	197	89.6	127	216	130	89	202	197
j_7	32.5	224	58.4	139	200	26	177	229	32.5	58.4
j_8	29.3	198	41	113	174	55.1	150	203	29.3	41
j_9	1	201	26.9	116	176	53	153	205	1	26.9
j_{10}	27.4	193	1	108	169	80.8	146	198	27.4	1
j_{11}	63.2	154	37.6	68.5	129	79	106	158	63.2	37.6
j_{12}	86.5	141	52.2	56	118	100	95.3	148	86.5	52.2
j_{13}	94.9	109	89.2	23	86.1	92.5	63	115	94.9	89.2
j_{14}	207	98.3	201	94.2	198	205	164	164	207	201
j_{15}	112	119	106	34.2	67.4	110	44.3	96.5	112	106
j_{16}	125	108	119	23	80.3	123	57.2	92.3	125	119
j_{17}	152	134	146	81.3	30.1	149	1.6	43.3	152	146
j_{18}	166	172	160	95.4	48.4	163	39.7	81.2	166	160
j_{19}	168	155	162	97.8	31	166	29	63.7	168	162
j_{20}	176	126	170	105	17.7	173	28.3	35.5	176	170
j_{21}	192	134	186	121	21.8	189	44.3	75.6	192	186
j_{22}	113	88	106	1	104	111	81	90	113	106
j_{23}	237	129	231	138	73.9	234	83.6	48.8	237	231
j_{24}	195	92	189	89.9	39.7	193	42.8	1	195	189
j_{25}	155	137	150	44.3	62.8	153	30.2	47	155	150

Table 4.7(cont'): Distance data [km].

	i_{11}	i_{12}	i_{13}	i_{14}	i_{15}	i_{16}	i_{17}	i_{18}	i_{19}	i_{20}
j_1	141	30.3	233	193	141	181	233	131	153	190
j_2	139	21.2	228	188	139	235	228	105	147	185
j_3	136	21.9	225	185	136	173	225	122	144	182
j_4	123	9	212	172	123	160	212	110	131	169
j_5	86.1	211	90.3	170	86.1	132	90.3	140	107	135
j_6	89.6	216	89	169	89.6	130	89	144	111	133
j_7	139	26	229	188	139	177	229	106	148	186
j_8	113	55.1	203	162	113	150	203	73.7	122	160
j_9	116	53	205	165	116	153	205	85.1	124	162
j_{10}	108	80.8	198	157	108	146	198	52.1	117	155
j_{11}	68.5	79	158	117	68.5	106	158	23.1	77	115
j_{12}	56	100	148	72	56	95.3	148	1	64.5	104
j_{13}	23	92.5	115	74.7	23	63	115	32.8	32.1	72.1
j_{14}	94.2	205	164	187	94.2	164	164	148	115	184
j_{15}	34.2	110	96.5	47.9	34.2	44.3	96.5	52.2	12.9	53.4
j_{16}	23	123	92.3	64.7	23	57.2	92.3	64.9	1	66.3
j_{17}	81.3	149	43.3	38.3	81.3	1.6	43.3	93.8	55.1	10.2
j_{18}	95.4	163	81.2	1	95.4	39.7	81.2	71	61.3	52.2
j_{19}	97.8	166	63.7	16.8	97.8	29	63.7	110	71.6	34.8
j_{20}	105	173	35.5	63.2	105	28.3	35.5	118	79.1	20.5
j_{21}	121	189	75.6	67.6	121	44.3	75.6	134	95	36.5
j_{22}	1	111	90	80.1	1	81	90	53.3	20.9	90.1
j_{23}	138	234	48.8	124	138	83.6	48.8	179	140	75.9
j_{24}	89.9	193	1	81.6	89.9	42.8	1	137	82.2	45.9
j_{25}	44.3	153	47	63.3	44.3	30.2	47	96.5	46.6	38.8

Table 4.7(cont'): Distance data [km].

	i_{21}	i_{22}	i_{23}	i_{24}	i_{25}	Port
j_1	58.5	227	85	141	131	235
j_2	31.8	229	57.7	139	105	216
j_3	72.3	200	98.3	136	122	214
j_4	60.5	213	91.5	123	110	194
j_5	199	1	193	86.1	140	137
j_6	202	5	197	89.6	144	138
j_7	32.5	224	58.4	139	106	242
j_8	29.3	198	41	113	73.7	189
j_9	1	201	26.9	116	85.1	206
j_{10}	27.4	193	1	108	52.1	144
j_{11}	63.2	154	37.6	68.5	23.1	146
j_{12}	86.5	141	52.2	56	1	116
j_{13}	94.9	109	89.2	23	32.8	108
j_{14}	207	98.3	201	94.2	148	164
j_{15}	112	119	106	34.2	52.2	93.4
j_{16}	125	108	119	23	64.9	97.7
j_{17}	152	134	146	81.3	93.8	56.5
j_{18}	166	172	160	95.4	71	64
j_{19}	168	155	162	97.8	110	60.9
j_{20}	176	126	170	105	118	45.6
j_{21}	192	134	186	121	134	7.7
j_{22}	113	88	106	1	53.3	130
j_{23}	237	129	231	138	179	48.2
j_{24}	195	92	189	89.9	137	52.9
j_{25}	155	137	150	44.3	96.5	51.8

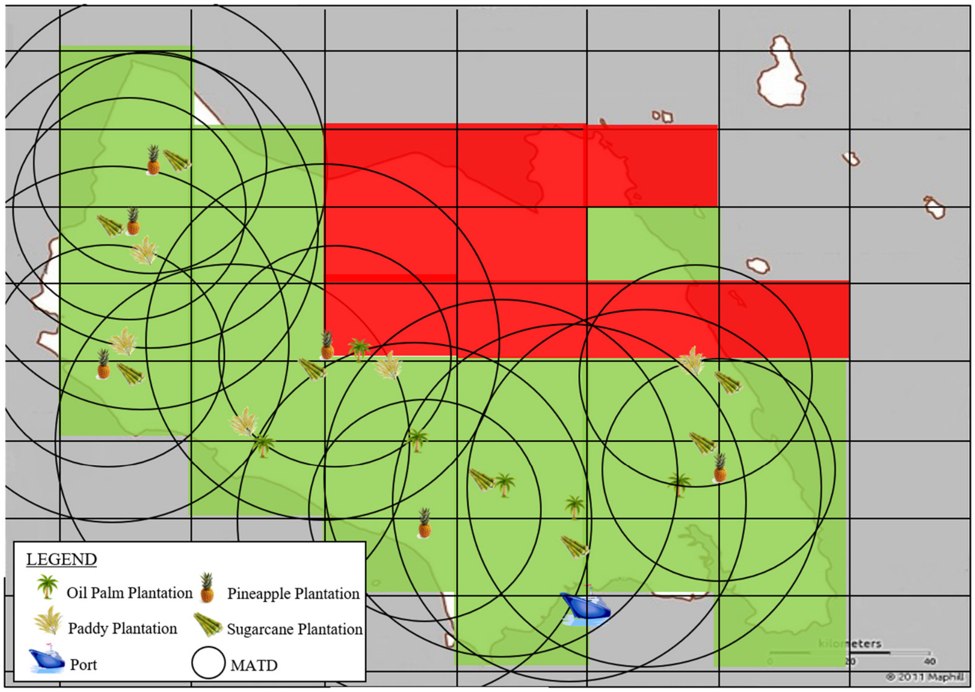

Figure 4.15: Superimposed feasible location after Phase II (Maphill, 2013).

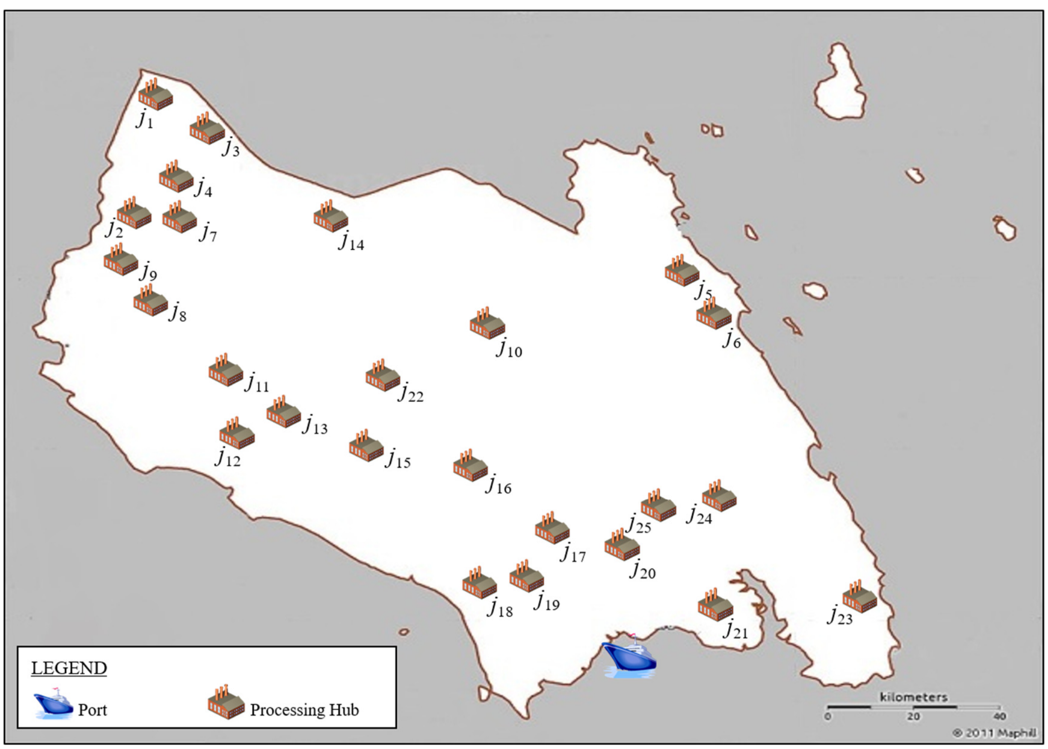

Figure 4.16: Geographical location for each potential hub (Maphill, 2013).

Table 4.8 shows the number of variables present in the model and the computational time required before and after the decomposition process. Despite the reduction in computation time is not significant for this case study, the results still show that the proposed approach is applicable to reduce the model-size of the multi-biomass supply chain problems (i.e., 67 % of variables are being reduced from the model). The improvement of computational time is expected to be more significant for larger case study. Aside from this, it is worth noting that the percentage error between the maximum C^{NP} obtained before and after decomposition is negligible (less than 1 %) for this case study.

Table 4.8: Computational performance before and after decomposition.

	Non-binary variables	Binary Variables	Computational Time [s]	C^{NP} [RM/y]
Original (consider 33 hubs)	2,311	33	0.09	7.98 x 10^8
After Phase I+II	751	25	0.08	7.98 x 10^8

4.5.3 Optimised results

The mathematical model is optimised to determine the maximal profit that can be gained, number of hubs to be set up, optimal location for each processing hub and optimal biomass allocation design for this case study. The optimised result is shown in Figure 4.17 (please refer Appendix Section A.1.1 and Section A.1.2 for the complete model coding and result).

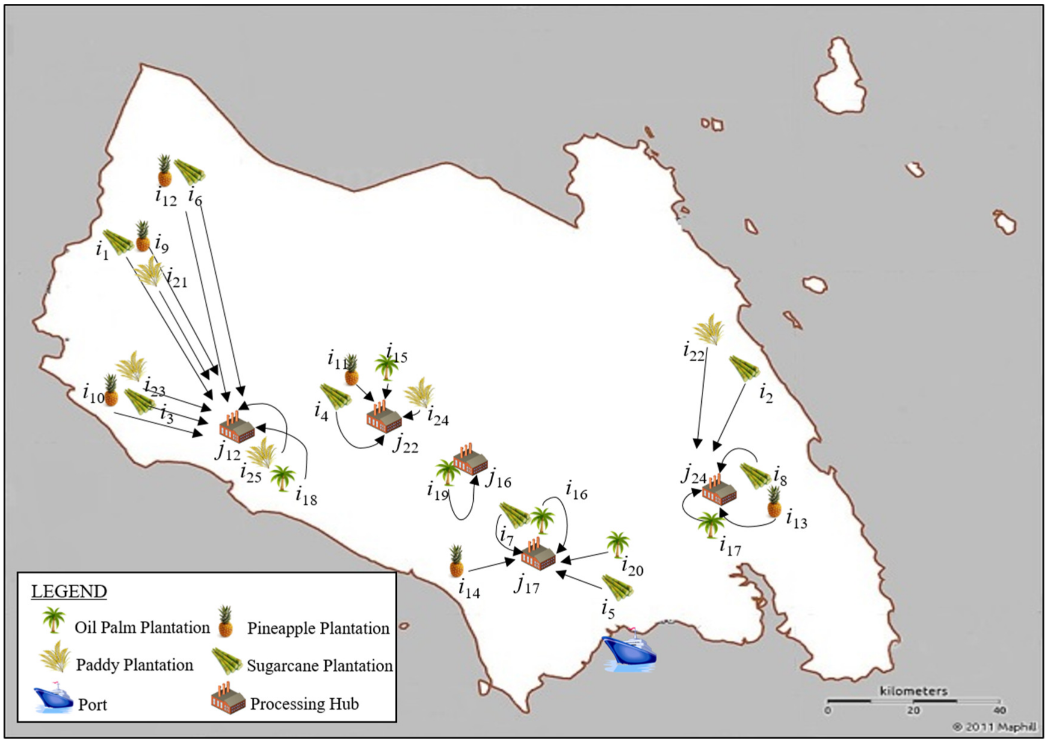

Figure 4.17: Optimal biomass allocation design (Maphill, 2013).

From Figure 4.17, it shows that the optimal number of processing hubs is five. If fewer hubs were built (< 5), some of the biomass will transported to a processing hub, which is located farther away from the source point. Therefore, higher transportation cost is expected (see Figure 4.18). On the other hand, if more hubs were built (> 5), the reduction of transportation cost is very insignificant and is unable to compensate the additional investment cost to set up these hubs. Thus, lower net profit, C^{NP} [RM/y] is obtained (see Figure 4.19).

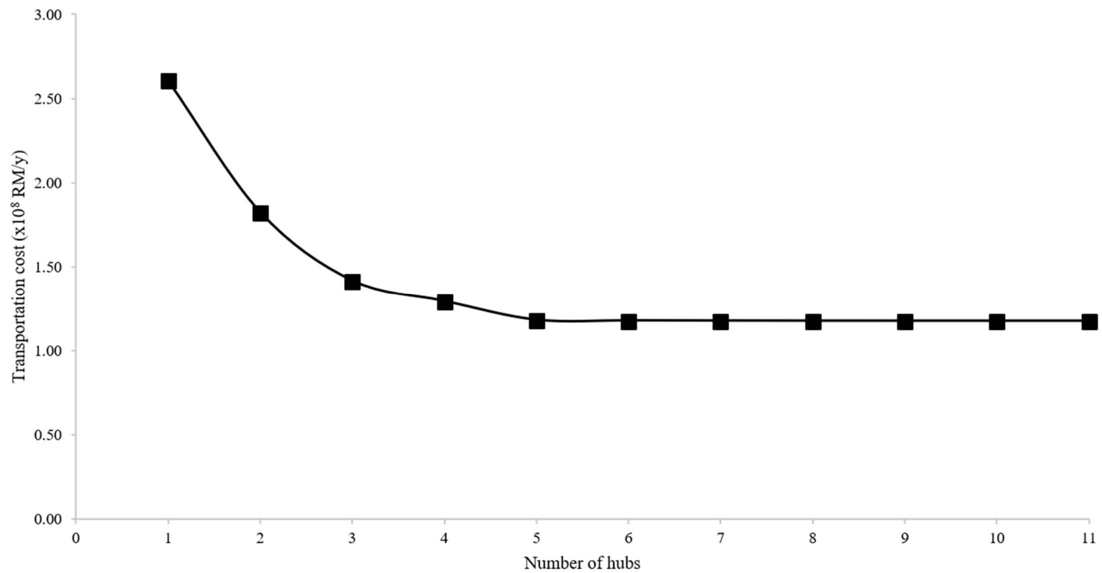

Figure 4.18: Transportation cost required for the synthesised biomass supply chain.

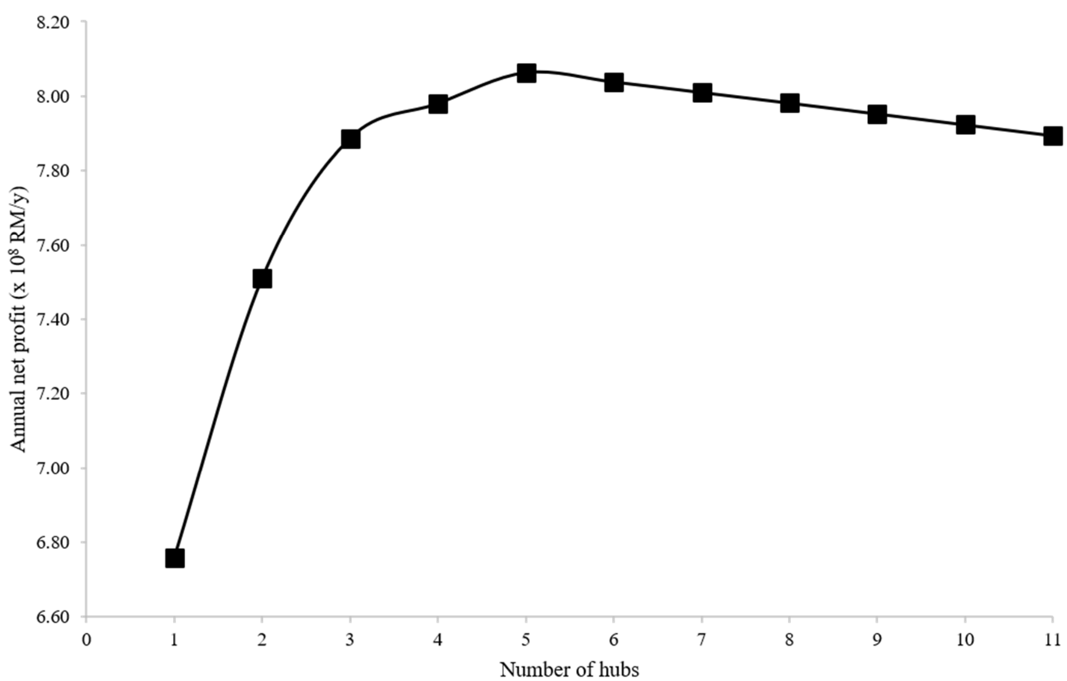

Figure 4.19: Net profit for the synthesised biomass supply chain.

4.5.4 Limitation

It is worth noting that the limitation of this proposed method is the low robustness of the obtained solution. For instance, the correlated cost function has to be reformulated when adding a new biomass or a new conversion technology into the model. In order to address this issue, proper planning of the model-size in the early stage is necessary:

I. Select all the available biomass, which has high EP.

II. Consider all the conventional or potential technology available in the study area into the model.

III. Ensure the economic data (i.e., material cost, equipment cost, operating cost, etc.) used in the model is up-to-date (regular revision of the data is recommended).

In addition, another main concern of separating the research problem into various sub-models during optimisation is the difficulty in ensuring global optimality of the model. For instance, the model could identify the best design for the processing hubs based on the current biomass availability. However, after allocating the biomass to the first plant, the remaining biomass availability might not be sufficient to support the same design in the second plant. This will be problematic especially when the process is highly-integrated (e.g., technology for a given biomass required by-products from another technology of other biomass). To address this issue, model iterations in Phase I should be conducted (see Figure 4.20). The correlated cost constant for each plant is generated based on the updated biomass availability. This can enhance the global optimality of the proposed model.

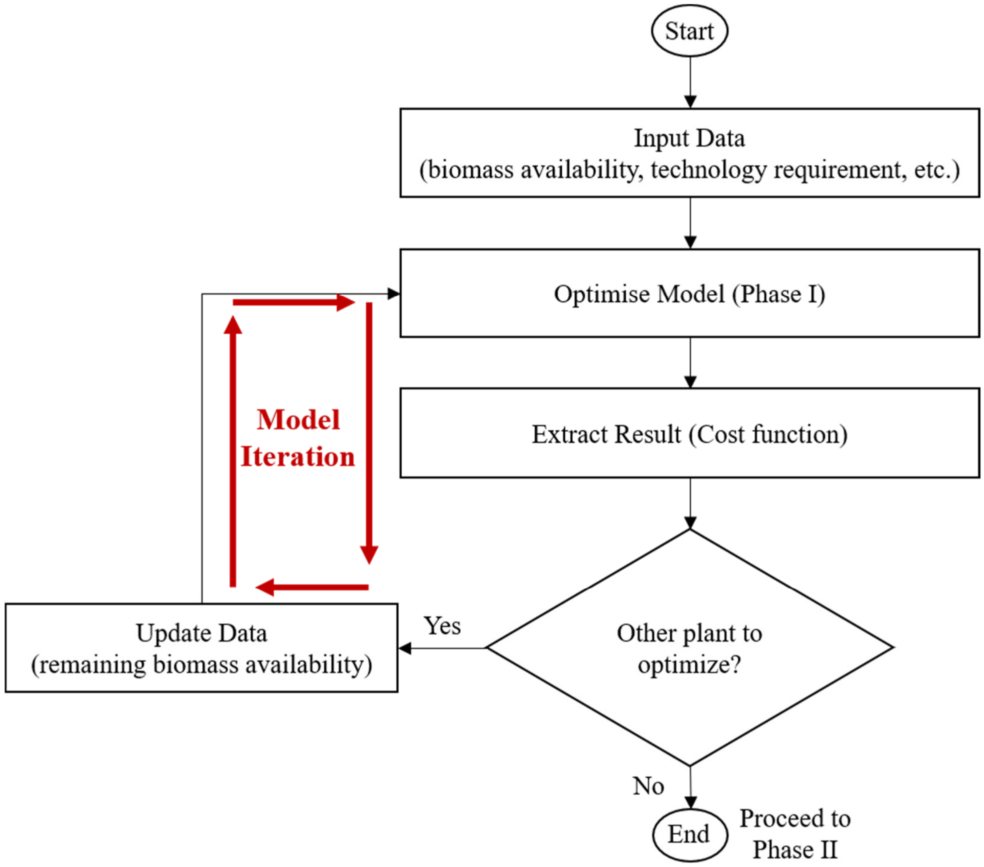

Figure 4.20: Sample iteration steps in Phase I.

Aside from this, the processing hub determination is highly influenced by the fragmentised area used during "area fragmentation". It is expected that smaller fragmentised area will lead to higher chance of obtaining global optimal. A Pareto analysis is conducted to investigate the effect of fragmentised area on annual net profit obtained and the total computational time required. As shown in Figure 4.21, higher profit is obtained when smaller fragmentised area is used (Please refer Appendix Section A.1.4 for the visualisation of "area fragmentation" for each case). As a trade-off, longer computational time is required. In this analysis, the highest annual net profit (i.e., RM 8.10 x 10^8) is obtained when study area is fragmentised into 100 km^2-zones. Despite the annual net profit determined in this work (when study area is fragmentised into 600 km^2-zones) is lower compared to the highest achievable net profit, but the error percentage is merely 0.5 %. More importantly, the computation time required in this work is significantly lower (almost 6 folds lower). Please refer Table 4.9 for the error percentage and the required computational time for each case. All these values indicate that the fragmentised area used in this work is acceptable.

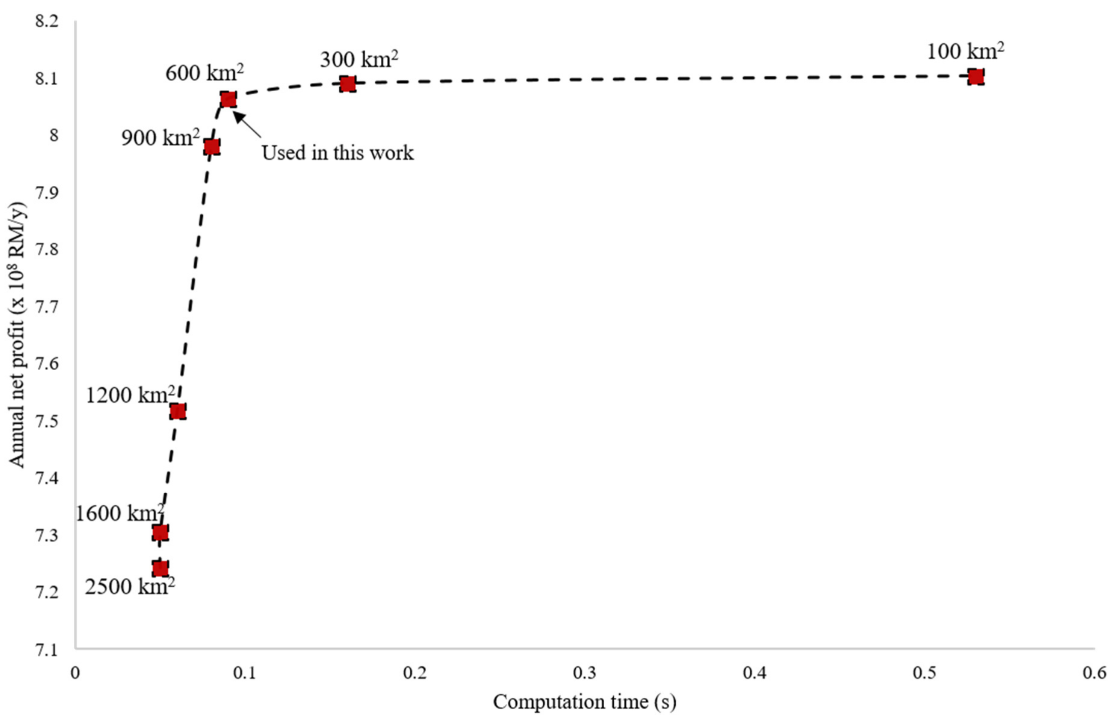

Figure 4.21: Pareto analysis for area fragmentation.

Table 4.9: Error percentage and computational time for each case.

Fragmentised Area [km^2]	Error Percentage [%]	Computational Time [s]
100	0.0	0.53
300	0.2	0.16
600	0.5	0.09
900	1.5	0.08
1200	7.2	0.06
1600	9.9	0.05
2500	10.6	0.05

4.6 Conclusion

This chapter has addressed the issue of solving a large-scale multiple biomass corridor problem. The main contributions of this work are stated as follow:

I. A novel P-graph aided two-stage optimisation model, which integrates P-graph framework and conventional mathematical modelling is proposed to solve the multi-biomass supply chain problem.

II. With the aid of P-graph's astonishing computing features and its visual interface, the users can determine the correlated cost function for each biomass easily and effectively.

III. Results shows that the proposed approach is applicable to reduce the model-size of the multi-biomass supply chain problems significantly (i.e., 67 %) in order to mitigate the computational burden.

IV. A multi-biomass supply chain, which integrates the use of palm oil biomass, paddy biomass, pineapple peels and sugarcane bagasse is synthesised. The available technologies for each biomass conversion are summarised.

V. A Pareto analysis is conducted to test the effect of fragmentised area used on total annual net profit gained. The result shows that the fragmentised area used in this work is acceptable.

In order to ensure the reliability of the proposed approach, regular revision on the input date is required. On top of that, this work can be extended by considering physical constraints of the vehicle (load and volume) into the model. This would provide a more accurate estimation of transportation cost, which therefore avoiding unnecessary loss of profit (see Chapter 4). Aside from this, more efforts have to be conducted in incorporating different environmental indexes and social indicators into the optimisation model (Chapter 5 and Chapter 6). Last but not least, the proposed approach has to be applied for larger-scale case study in order to test its reliability and robustness.

Chapter 5:

Transportation Decision-Making

5.1 Introduction

In this chapter, the mathematical model proposed in the previous chapter is modified in order to solve the multi-biomass supply chain synthesis problem with the consideration of vehicle capacity constraint (weight and volume). On top of that, carbon emission penalty is also introduced in the model in order to evaluate the environmental impact in the supply chain. The entire problem is modelled through mixed integers linear programming (MILP) with the aim of maximising the overall profit, at the same time ensuring the minimal CO_2 emission. The comparison between these two models will be presented as well. In order to fill the gap of lacking user-friendly decision-making tool for the transportation design in supply chain management, a novel graphical decision-making tool, called smart vehicle selection (SVS) diagram is proposed. The diagrams are constructed based on the optimised results obtained from the formulated model. The user manual for the proposed decision-making tool is given in this paper. Besides, five sets of sensitivity analysis are conducted to identify the sensitivity of the assumed realistic factors (i.e., terrain profile, weather changes, traffic congestion, fuel price fluctuation and individual environmental preference) to the optimal results obtained from the proposed tools. This chapter is arranged as follow. Section 5.2 presents the problem statement and summarise all the assumptions used in this work while Section 5.3 outlines the methodology of the research work in this chapter. Section 5.4 shows the model formulation for this problem. The development of decision-making tool is presented in Section 5.5. In Section 5.6, background of the case study is revised. The description of the sensitivity analysis is given in Section 5.7.

It is then followed by the results and discussion in Section 5.8. Finally, concluding remarks are stated in Section 5.9.

5.2 Problem Statement

The problem described in this work aim to determine the optimal biomass allocation networks and the optimal transportation decisions that minimise transportation cost and reduce carbon emission. It is formally stated as follows: given a set of biomass types *r* supplied from a set of source points *i* is planned to be delivered through a set of transportation modes *m* to a set of processing hubs *j*. Then, it is converted into a set of products *p* via a set of technologies *t* and *t'* and delivered to a set of customers *k* through a set of transportation mode *m'*. All the intermediates are denoted as *l*. The superstructure of the model is now modified as Figure 5.1. In order to provide readers a better understanding and insight into the proposed research problem, several underlying assumptions are stated:

I. Demand uncertainties are insignificant within a given time horizon (a year).

II. Decentralised transportation is applied in this problem. The resources of transportation (e.g., number of vehicle) available in market are not limited.

III. Loading and unloading lead times are constant for a given transportation mode.

IV. Average driving speed is used in the model. Basically, smaller truck has a higher driving speed than the bigger truck.

V. 3-D space allocation issue is not considered in this work (e.g., a 1 m^3 cube compartment cannot hold a 1 m^3 sphere).

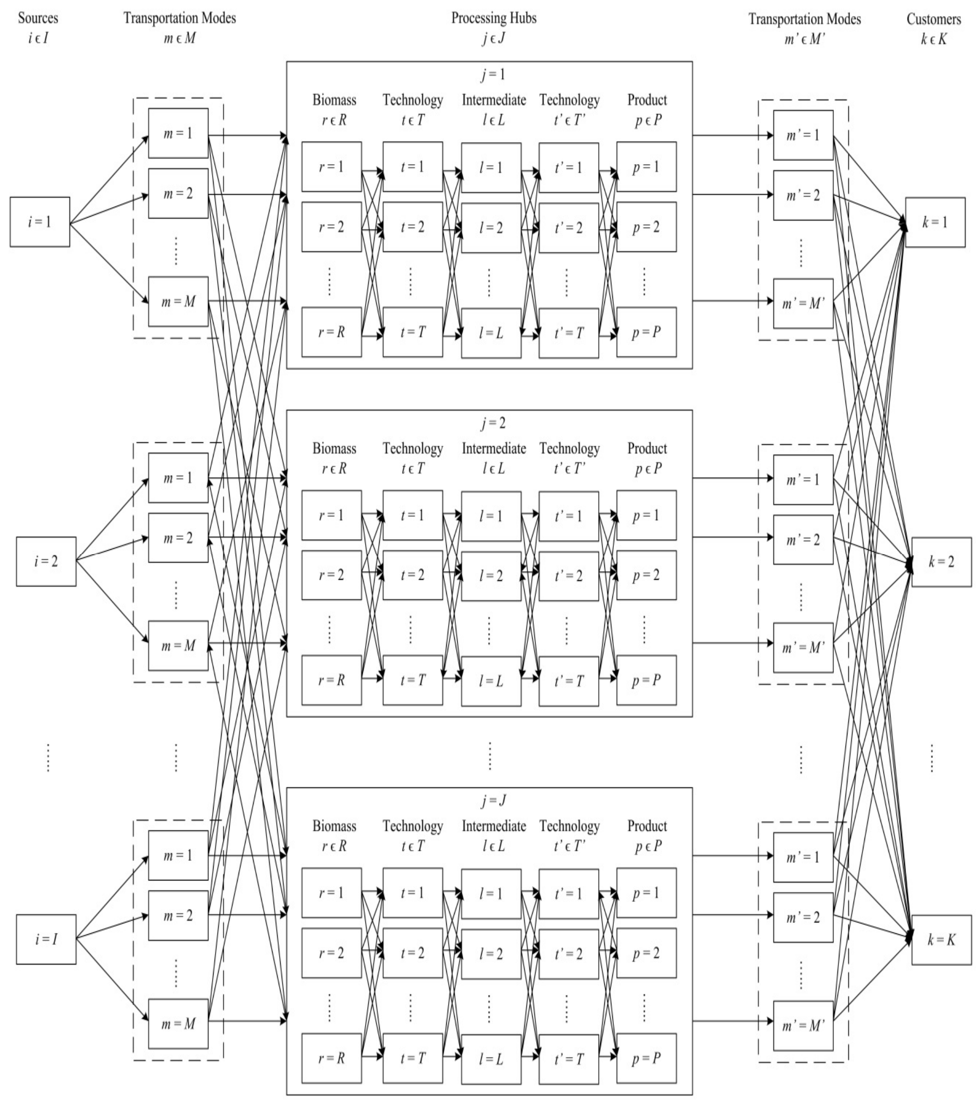

Figure 5.1: Generic superstructure of the proposed model (modified from Figure 4.5).

5.3 Methodology

The overview of the research method for this chapter is shown in Figure 5.2. The model is reformulated in order to consider different type of transportation modes for the vehicle selections. The criteria for the vehicle selection process is based on its economic performance (i.e., capital cost, total fuel consumption, etc.) and environmental performance (i.e., total CO_2 emission). The developed model is described in detail in Section 5.4 while the conceptual idea for the development of the proposed decision-making tool is discussed in Section 5.5. Besides, sensitivity study is conducted to check the sensitivity of the assumed parameters. The description of the sensitivity analysis is stated in Section 5.7.

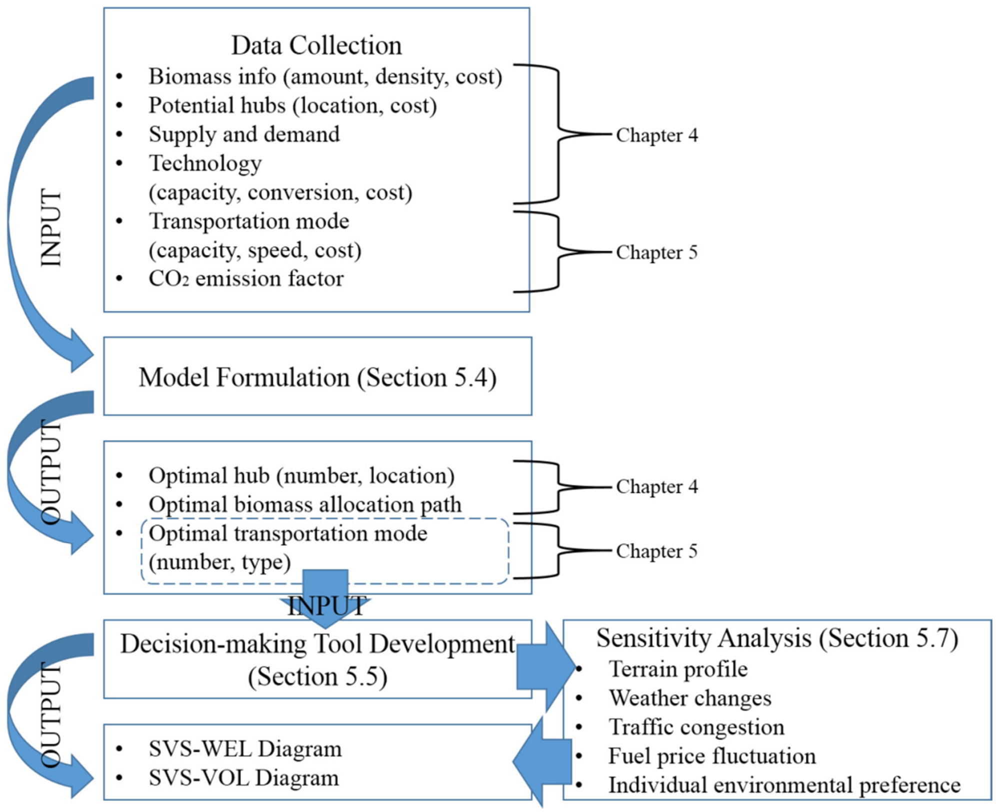

Figure 5.2: Overview of research method for Chapter 5 (reproduced from Figure 3.3).

5.4 Model Formulation

Generally, the model formulated in Chapter 4 is modified in order to incorporate the vehicle capacity constraint. The problem is modelled through MILP, and will be solved by using Lingo v14.0 (Lingo, 2015). The description of the modified formulations, including constraint setting and objective functions are given below:

5.4.1 Constraint setting

5.4.1.1 Material flow constraint

Equations (4.3) and (4.4) are revised to consider different options for transportation modes (*m* or *m'*):

$$\sum_m \sum_j F_{r,i,m,j} \leq \mathrm{F}_{r,i} \qquad \forall r \in R, \forall i \in I, \tag{5.1}$$

$$\sum_{m'} \sum_k F_{p,j,m',k} \leq F_{p,j} \quad \forall p \in P, \forall j \in J, \tag{5.2}$$

Equations (4.6) to (4.9) which define the material balance in the processing hub *j* and Equations (4.10) and (4.11) which determines the selection of possible processing hub *j* will remain the same, while Equation (4.5) which concerns the transportation between source *i* and hub *j* is re-defined as:

$$\sum_i \sum_m F_{r,i,m,j} = F_{r,j} \quad \forall r \in R, \forall j \in J \tag{5.3}$$

5.4.1.2 Operating time constraint

Besides, Constraints (5.4) and (5.5) are added in order to set a time constraint to the problem, where the total operating hour per day cannot exceed the maximum allowable operating hour, $\mathrm{OH}^{\mathrm{Max}}$ [h/d]:

$$num^{\mathrm{Trip}} \times \mathrm{OH}_{i,m,j} \leq \mathrm{OH}^{\mathrm{Max}} \quad \forall i \in I, \forall m \in M, \forall j \in J \tag{5.4}$$

$$num^{\mathrm{Trip}} \times \mathrm{OH}_{j,m',k} \leq \mathrm{OH}^{\mathrm{Max}} \quad \forall j \in J, \forall m' \in M', \forall k \in K \tag{5.5}$$

where num^{Trip} [trips/d] refers to the number of trips travelled per day while $OH_{i,m,j}$ [h/trip] and $OH_{j,m',k}$ [h/trip] refer to the delivery lead time from source *i* to hub *j* and hub *j* to customer *k* respectively. These constraints are set to comply with regulation

(EC) 561/2006 which limit the maximum travel time per day. In fact, this is crucial to ensure vehicle's operating performance and driver's heath are both in good condition. In general, a 40 minutes break should be taken for every 4 hours travel (EC, 2014).

5.4.1.3 Vehicle capacity constraint

In this work, two vehicle capacity constraints are taken into consideration, i.e., weight limit and volume limit. Generally, weight regulation is set due to several safety concerns, while volume limit appears due to the finite space of vehicle's compartment (Obrien et al., 2012). Both limits are defined as follows:

$$\sum_r F_{r,i,m,j}^{\text{Weight}} \leq \text{Cap}_m^{\text{Weight}} \quad \forall i \in I, \forall m \in M, \forall j \in J \tag{5.6}$$

$$\sum_p F_{p,j,m',k}^{\text{Weight}} \leq \text{Cap}_{m'}^{\text{Weight}} \quad \forall j \in J, \forall m' \in M', \forall k \in K \tag{5.7}$$

where $\text{Cap}_m^{\text{Weight}}$ [t/trip]and $\text{Cap}_{m'}^{\text{Weight}}$ [t/trip] refer to the weight limit of the vehicle; $\sum_r F_{r,i,m,j}^{\text{Weight}}$ [t/d] refers to the weight of biomass *r* that is being delivered from source *i* to hub *j* via transportation mode *m* per day; while $\sum_p F_{p,j,m',k}^{\text{Weight}}$ [t/d] refers to the weight of product *p* that is being delivered from hub *j* to customer *k* via transportation mode *m'* per day. Equations (5.6) and (5.7) are used for weight-limiting problem.

$$\sum_r F_{r,i,m,j}^{\text{Volume}} \leq \text{Cap}_m^{\text{Volume}} \quad \forall i \in I, \forall m \in M, \forall j \in J \tag{5.8}$$

$$\sum_p F_{p,j,m',k}^{\text{Volume}} \leq \text{Cap}_{m'}^{\text{Volume}} \quad \forall j \in J, \forall m' \in M', \forall k \in K \tag{5.9}$$

where $\text{Cap}_m^{\text{Volume}}$ [m^3/trip] and $\text{Cap}_{m'}^{\text{Volume}}$ [m^3/trip] refer to the volume limit of the vehicle; $\sum_r F_{r,i,m,j}^{\text{Volume}}$ [m^3/d] refers to the volume-capacity of biomass *r* that is being delivered from source i to hub j via transportation mode m per day; while$\sum_p F^{\text{Volume}}_{p,j,m',k}$ [m^3/d] refers to the volume-capacity of product p that is being delivered from hub j to customer k via transportation mode m' per day. Equations (5.8) and (5.9) are used for volume-limiting problem. These constraints will affect the total number of trip required and the total number of vehicle required (refer to Section 5.4.2.2 and Section 5.4.2.3).

5.4.2 Transportation function

The equations used to determine the delivery lead time, number of trips required and number of vehicle required and annual transportation cost are stated and described accordingly in the three subsections below:

5.4.2.1 Delivery lead time

Delivery lead time ($\text{OH}_{i,m,j}$ [h/trip] and $\text{OH}_{j,m',k}$ [h/trip]) is one of the main economic variables for transportation system (Gronalt & Rauch, 2007). It is highly dependent on traveling distance and travelling speed of vehicles (Gold & Seuring, 2011).

$$\text{Sp}^{\text{Mean}}_{m} = \frac{\text{Sp}^{\text{Max}}_{m} + \text{Sp}^{\text{Min}}_{m}}{2} \quad \forall m \in M \tag{5.10}$$

$$\text{Sp}^{\text{Mean}}_{m'} = \frac{\text{Sp}^{\text{Max}}_{m'} + \text{Sp}^{\text{Min}}_{m'}}{2} \quad \forall m' \in M' \tag{5.11}$$

where Sp^{Max}_{m} [km/h] and $Sp^{\text{Max}}_{m'}$ [km/h] refer to the maximum travelling speed that can be achieved by the transport mode m and m' when it is empty-filled; $\text{Sp}^{\text{Min}}_{m}$ (km/h) and $\text{Sp}^{\text{Min}}_{m'}$ [km/h] refer to the minimum travelling speed that can be achieved by transport mode m and m' when it is fully-loaded. In this work, vehicles are assumed to be driven under a constant travelling speed (refer to Assumption 4). This estimated travelling speed is obtained from Equations (5.10) and (5.11).

$$\mathrm{OH}_{i,m,j} = \frac{2 \times \mathrm{d}_{i,j}}{\mathrm{Sp}_m^{\mathrm{Mean}}} + \mathrm{DT}_m \qquad \forall i \in I, \forall m \in M, \forall j \in J \tag{5.12}$$

$$\mathrm{OH}_{j,m',k} = \frac{2 \times \mathrm{d}_{j,k}}{\mathrm{Sp}_{m'}^{\mathrm{Mean}}} + \mathrm{DT}_{m'} \qquad \forall j \in J, \forall m' \in M', \forall k \in K \tag{5.13}$$

Equations (5.12) and (5.13) are used to determine the delivery lead time. It is worth mentioning that the delivery is not a one-way travel. The return ride has to be taken into account when determining the delivery lead time. Therefore, the travelling distance ($\mathrm{d}_{i,j}$ [km/trip] and $\mathrm{d}_{j,k}$ [km/trip]) is multiplied by two in both Equations (5.12) and (5.13). In addition, the delay time (DT_m [h/trip] and $\mathrm{DT}_{m'}$[h/trip]) due to the loading and unloading processes is considered in this model as well.

5.4.2.2 Number of trip required

Due to the physical capacity constraints set in Constraints (5.6) to (5.9), the amount of material that can be transported per vehicle per trip is limited. The required number of trips in order to deliver all materials to the destination is defined as follow:

$$num_{i,m,j}^{\mathrm{Trip}} \geq \left\lceil \frac{\sum_r F_{r,i,m,j}^{\mathrm{Weight}}}{\mathrm{Cap}_m^{\mathrm{Weight}}} \right\rceil \qquad \forall i \in I, \forall m \in M, \forall j \in J \tag{5.14}$$

$$num_{j,m',k}^{\mathrm{Trip}} \geq \left\lceil \frac{\sum_r F_{p,j,m',k}^{\mathrm{Weight}}}{\mathrm{Cap}_{m'}^{\mathrm{Weight}}} \right\rceil \qquad \forall j \in J, \forall m' \in M', \forall k \in K \tag{5.15}$$

A noteworthy fact is that $num_{i,m,j}^{\mathrm{Trip}}$ [trip/d] and $num_{j,m',k}^{\mathrm{Trip}}$ [trip/d] must be positive integers, $num_{i,m,j}^{\mathrm{Trip}} \in \mathbb{Z}^+, num_{j,m',k}^{\mathrm{Trip}} \in \mathbb{Z}^+$. Stopping in the mid-way is meaningless for the proposed problem. Therefore, the decimal numbers have to be rounded up to the nearest larger integer. Ceil functions $\lceil \dots \rceil$ are used as the mathematical expression for this round-up process. Equations (5.14) and (5.15) are used when weight is the limiting factor.

$$num_{i,m,j}^{\text{Trip}} \geq \left\lceil \frac{\sum_r F_{r,i,m,j}^{\text{Volume}}}{\text{Cap}_m^{\text{Volume}}} \right\rceil \qquad \forall i \in I, \forall m \in M, \forall j \in J \tag{5.16}$$

$$num_{j,m',k}^{\text{Trip}} \geq \left\lceil \frac{\sum_r F_{p,j,m',k}^{\text{Volume}}}{\text{Cap}_{m'}^{\text{Volume}}} \right\rceil \qquad \forall j \in J, \forall m' \in M', \forall k \in K \tag{5.17}$$

Equations (5.16) and (5.17) are another two equations used to determine the number of trip required for a volume limiting problem. In general, high-density materials will hit the weight limit before filling up all the available volume capacity (weight-limiting). Conversely, low-density material will fully occupy the space before exceeding the weight limit (volume-limiting). Therefore, it is important to identify which parameter is the limiting factor of the problem.

5.4.2.3 Number of vehicle required

Due to the restriction set by Constraints (5.4) and (5.5), the number of trips that can be completed per vehicle per day is limited. Therefore, the maximum number of trips that can be completed by each vehicle per day, $\text{num}_{i,m,j}^{\text{Trip\_Max}}$ [trip/d] and $\text{num}_{j,m',k}^{\text{Trip\_Max}}$[trip/d] are described as:

$$\text{num}_{i,m,j}^{\text{Trip\_Max}} = \left\lfloor \frac{\text{OH}^{\text{Max}}}{\text{OH}_{i,m,j}} \right\rfloor \qquad \forall i \in I, \forall m \in M, \forall j \in J \tag{5.18}$$

$$\text{num}_{j,m',k}^{\text{Trip\_Max}} = \left\lfloor \frac{\text{OH}^{\text{Max}}}{\text{OH}_{j,m',k}} \right\rfloor \qquad \forall j \in J, \forall m' \in M', \forall k \in K \tag{5.19}$$

The value of the number of trips must be a positive integer, $num^{\text{Trip\_Max}} \in \mathbb{Z}^{+}$. However, instead of using ceil function, the decimal number has to be rounded down to the nearest smaller integer. This is to ensure the total operating h in a day is capped at the OH^{Max}[h/d]. Thus, floor functions $\lfloor \dots \rfloor$ are used as the mathematical expression for the round-down process.

Equations (5.20) and (5.21) are used to determine the number of vehicle required, $num_{i,m,j}^{\text{Vehicle}}$ (and $num_{j,m',k}^{\text{Vehicle}}$) in the problem. Again, decimal number of vehicle is meaningless,($num_{i,m,j}^{\text{Vehicle}}$ and $num_{j,m',k}^{\text{Vehicle}} \in \mathbb{Z}^{+}$). In order to ensure all materials are able to be delivered to their destination within a given time horizon, the decimal number has to be rounded up. Hence, ceil functions are used:

$$num_{i,m,j}^{\text{Vehicle}} \geq \left\lceil \frac{num_{i,m,j}^{\text{Trip}}}{\text{num}_{i,m,j}^{\text{Trip\_Max}}} \right\rceil \quad \forall i \in I, \forall m \in M, \forall j \in J \tag{5.20}$$

$$num_{j,m',k}^{\text{Vehicle}} \geq \left\lceil \frac{num_{j,m',k}^{\text{Trip}}}{\text{num}_{j,m',k}^{\text{Trip\_Max}}} \right\rceil \quad \forall j \in J, \forall m' \in M', \forall k \in K \tag{5.21}$$

5.4.3 Economic evaluation

Equations (4.13) and (4.15) which used to determine the annual gross profit and annual hub investment cost are remain unchanged. However, Equations (4.14) which defined the annual transportation is reformulated as:

$$C^{\text{Tr}} = C^{\text{Tr\_OPEX}} + C^{\text{Tr\_CAPEX}} \tag{5.22}$$

C^{Tr} [RM/y] is obtained by summation of operating expenditure (OPEX), $C^{\text{Tr\_OPEX}}$ [RM/y] and capital expenditure (CAPEX), $C^{\text{Tr\_CAPEX}}$ [RM/y] in transportation system (Gasol et al., 2009). Their components are described as:

$$C^{\text{Tr\_OPEX}} = (C^{\text{Labour}} + C^{\text{Mileage}} + C^{\text{Maintc}}) \times \text{OPD} \tag{5.23}$$

$$C^{\text{Tr\_CAPEX}} = C^{\text{Proc}} \tag{5.24}$$

OPEX concerns the ongoing operating cost required to deliver the materials to their destinations, including labour cost (C^{Labour} [RM/d]), mileage cost (C^{Mileage} [RM/d]) and maintenance cost (C^{Maintc} [RM/y]), while CAPEX concerns the annualised investment cost for the procurement of vehicles, C^{Proc}[RM/y].

$$C^{\text{Labour}} = \text{HW} \times \left\{ \sum_i \sum_m \sum_j (\text{OH}_{i,m,j} \times num_{i,m,j}^{\text{Trip}}) + \sum_j \sum_{m'} \sum_k (\text{OH}_{j,m',k} \times num_{j,m',k}^{\text{Trip}}) \right\} \tag{5.25}$$

Labour cost is determined by multiplying the total operating hour to the hourly wage, HW [RM/h] of the workers.

$$C^{\text{Mileage}} = 2\text{C}^{\text{Fuel}} \times \left\{ \sum_i \sum_m \sum_j (\text{d}_{i,j} \times num_{i,m,j}^{\text{Trip}} \times \text{rate}_m^{\text{Fuel}}) + \sum_j \sum_{m'} \sum_k (\text{d}_{j,k} \times num_{j,m',k}^{\text{Trip}} \times \text{rate}_{m'}^{\text{Fuel}}) \right\} \tag{5.26}$$

Mileage cost concerns about the total fuel price required for the delivery. It is determined by multiplying the total distance travelled to the fuel consumption rate of the vehicle, $\text{rate}_m^{\text{Fuel}}$ [L/km] and $\text{rate}_{m'}^{\text{Fuel}}$ [L/km] and fuel price, C^{Fuel} [RM/L].

$$C^{\text{Maintc}} = 2 \times \left\{\sum_i \sum_m \sum_j (\text{d}_{i,j} \times num_{i,m,j}^{\text{Trip}} \times \text{C}_m^{\text{Repair}}) + \sum_j \sum_{m'} \sum_k (\text{d}_{j,k} \times num_{j,m',k}^{\text{Trip}} \times \text{C}_{m'}^{\text{Repair}})\right\} \quad (5.27)$$

Maintenance cost of the vehicle is estimated according to the total distance travelled, where $\text{C}_m^{\text{Repair}}$ [RM/km] and $\text{C}_{m'}^{\text{Repair}}$ [RM/km] refer to the estimated repair and maintenance cost of vehicle per km of distance travelled.

$$C^{\text{Proc}} = \sum_i \sum_m \sum_j (num_{i,m,j}^{\text{Vehicle}} \times \frac{\text{C}_m^{\text{Proc}}}{\text{LS}_m^{\text{Tr}}}) + \sum_j \sum_{m'} \sum_k (num_{j,m',k}^{\text{Vehicle}} \times \frac{\text{C}_{m'}^{\text{Proc}}}{\text{LS}_{m'}^{\text{Tr}}}) \quad (5.28)$$

where C_m^{Proc} [RM] and $\text{C}_{m'}^{\text{Proc}}$ [RM] refer to the procurement cost of vehicle. Note that the procurement cost is annualised by dividing it to an estimated life span of vehicle, LS_m^{Tr} [y] and $\text{LS}_{m'}^{\text{Tr}}$ [y].

5.4.4 Environmental evaluation

In order to assess and evaluate progress towards more sustainable systems, proper monitoring and evaluation of the environmental impact is essential (Klemeš et al., 2012). The total carbon footprint, CF^{Total} [m^2/(t/y)] of the supply chain is considered to evaluate the environmental performance of the multi-biomass supply chain. The value of CF^{Total} [m^2/(t/y)] gives a general idea of the plantation required to compensate the environmental impact caused by a unit flow of material. Note that, this work only considers the total carbon footprint (CF) of the transportation activity in the supply chain. It is formulated as:

$$CF^{\text{Total}} = \frac{1}{\sum_r \sum_i F_{r,i}} \times \left\{(1 - \text{frac}^{\text{ab\_Ocean}}) \times \frac{TCE^{\text{Tr}}}{\text{Abs}^{\text{CO}_2}}\right\} \quad (5.29)$$

where $\mathrm{frac}^{\mathrm{ab\_Ocean}}$ [%] is the fraction of CO_2 absorbed by ocean; TCE^{Tr} [tCO_2/y] is the total carbon emission resulted from transportation; Abs^{CO_2} [$tCO_2/(m^2.y)$] is the CO_2 absorption rate by plantation. TCE^{Tr} is dependent on the transportation mode and distance travelled. It can be determined via equation below:

$$TCE^{\mathrm{Tr}} = \frac{2}{10^6} \times \mathrm{OPD} \times \left\{\sum_i \sum_m \sum_j (\mathrm{d}_{i,j} \times num^{\mathrm{Trip}}_{i,m,j} \times \mathrm{fac}^{CO_2}_m) + \sum_j \sum_{m'} \sum_k (\mathrm{d}_{j,k} \times num^{\mathrm{Trip}}_{j,m',k} \times \mathrm{fac}^{CO_2}_{m'})\right\} \tag{5.30}$$

where $\mathrm{fac}^{CO_2}_m$ [gCO_2/km] is the carbon emission factor for transportation mode *m* and $\mathrm{fac}^{CO_2}_{m'}$ [gCO_2/km] is the carbon emission factor for transportation mode *m'*.

5.4.5 Multi-objective optimisation

This model aims to determine a compromise solution for economic-environmental decision in SCM. In order to convert the multi-objectives optimisation problem into single objective optimisation problem, carbon emission penalty ($C^{\mathrm{Penalty\_CO_2}}$ [RM/y]) is introduced to estimate the additional payment required recover the damaged done to the environment. Among all the available carbon pricing methods, the quantification approach proposed by Zhou et al. (2015) is chosen. The significant merit of this approach is that the quantification process has considered both regional ecological and economic factors (Zhou et al., 2015). The quantification method is shown as below:

$$C^{\mathrm{Penalty\_CO_2}} = \sum_r \sum_i F_{r,i} \times CF \times \mathrm{C}^{\mathrm{Plantt}} \tag{5.31}$$

$$\mathrm{C}^{\mathrm{Plantt}} = \left(\mathrm{C}^{\mathrm{Fuel\_Plantt}} + \mathrm{C}^{\mathrm{Fert}} + \mathrm{C}^{\mathrm{Utility\_Plantt}} + \mathrm{C}^{\mathrm{Labour\_Plantt}}\right)/\mathrm{LS}^{\mathrm{Plantt}} \tag{5.32}$$

where C^{Plantt} [RM/(m^2.y)] is the plantation cost. $C^{\text{Fuel\_Plantt}}$ [RM/m^2] is the fuel cost required for plantation; C^{Fert} [RM/m^2] is the fertilising cost required for plantation; $C^{\text{Utility\_Plantt}}$ [RM/m^2] is the utility cost required for plantation; $C^{\text{Labour\_Plantt}}$ [RM/m^2] is the labour cost required for plantation; LS^{Plantt} [y] is the estimated life span of the plantation.

Therefore, Equation (4.17) is revised to take into account of the carbon emission penalty determined above. The two objective functions are now merged:

$$\max C^{\text{NP}} = C^{\text{GP}} - C^{\text{Inv\_Hub}} - C^{\text{Tr}} - C^{\text{Penalty\_CO}_2} \quad (5.33)$$

5.5 Decision-Making Tool Development

A user-friendly decision-making tool is important for decision-makers to put research output into practise. Therefore, a graphical decision-making tool, called "smart vehicle selection (SVS) diagram" is proposed in this chapter. The conceptual idea of developing this diagram and the description of how the diagram works are explained in the subsections below:

5.5.1 Concept of SVS diagrams

The discussion regarding to the physical limits of the vehicle (see descriptions for Equations (5.6) to (5.9) and Equations (5.14) to (5.17)) inspires the main concept of the SVS diagram. The SVS diagram is constructed based on the travelling distance and capacity of materials. Since this paper concerns the weight limit and volume limit of the vehicle, two versions of SVS diagram are developed, i.e., SVS-weight-limiting

(SVS-WEL) diagram and SVS-volume-limiting (SVS-VOL) diagram. Figure 5.3 outlines the SVS-WEL diagram and SVS-VOL diagram for truck A and truck B.

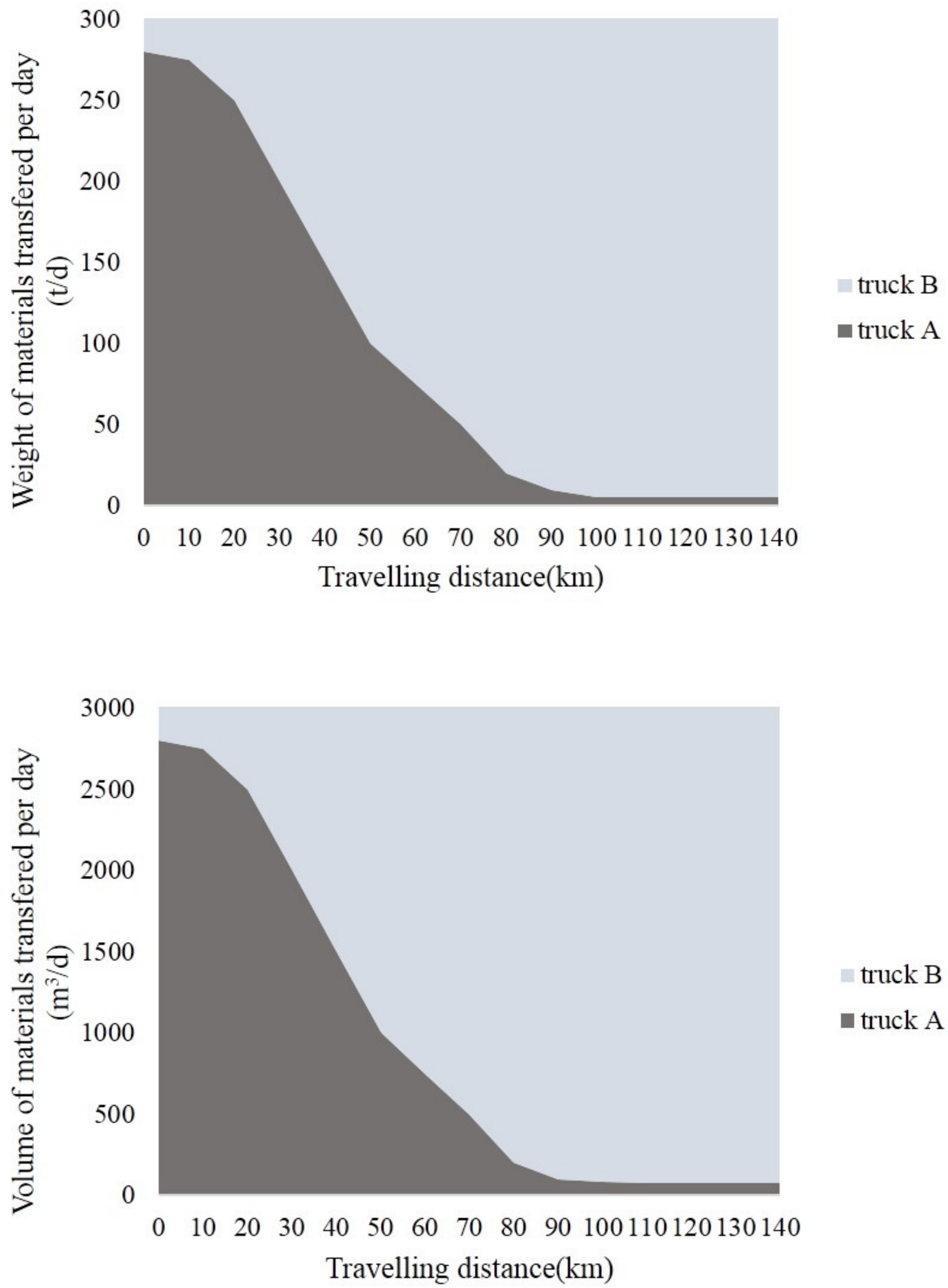

Figure 5.3: Outline of (T) SVS-WEL diagram; (B) SVS-VOL diagram.

Both diagrams share a same x-axis, which refers to the travelling distance between source (start point) and sink (end point). However, y-axis shows differently in these diagrams. In SVS-WEL diagram, y-axis is representing as the weight-capacity of the material to be transported per day; while the y-axis in SVS-VOL diagram is referring to the volume-capacity of the material to be transported per day. Each (x, y) point in the diagram defines a sub-problem. As shown in Figure 5.3, these sub-problems are shaded with different colour. Each colour indicates the optimal transportation mode to be used in that particular sub-problem. For instance, truck B is the best transportation mode to deliver 200 t/d of weight-limiting material (WLM) to customer which located 60 km away from the hub (in SVS-WEL); truck A is more cost effective and environmental friendlier to deliver 500 m^3/d of volume-limiting material (VLM) to customer which located 60 km away from hub (in SVS-VOL). These diagrams are constructed based on the optimised results obtained from the mathematical model formulated in Section 5.4 (using different sets of delivered amount and travelling distance) (please refer to Appendix Section A.2 for the model coding and result). With the aid of these diagrams, users can determine the optimal transportation mode directly without re-running the mathematical model, provided that the transportation distance and the total amount of material flow between the source and sink are known.

WLM refers to materials which exceed the weight limit before filling up all the available space of the vehicle. SVS-WEL diagram should be used for these materials. Conversely, VLM refers to materials which exceed the volume limit before reaching the maximum load limit. SVS-VOL diagram should be used for these materials. In order to identify which category that the materials belong to, Figure 5.4 is used. It shows the weight-volume line for the vehicle (solid line) and the transported materials (dotted line). The gradient indicates its bulk density. The bulk density of the vehicle capacity (ρ_m [t/m^3] and $\rho_{m'}$ [t/m^3]) is defined as:

$$\rho_m = \frac{\text{Cap}_m^{Weight}}{\text{Cap}_m^{Volume}} \quad \forall m \in M \tag{5.34}$$

$$\rho_{m'} = \frac{\text{Cap}_{m'}^{Weight}}{\text{Cap}_{m'}^{Volume}} \quad \forall m' \in M' \tag{5.35}$$

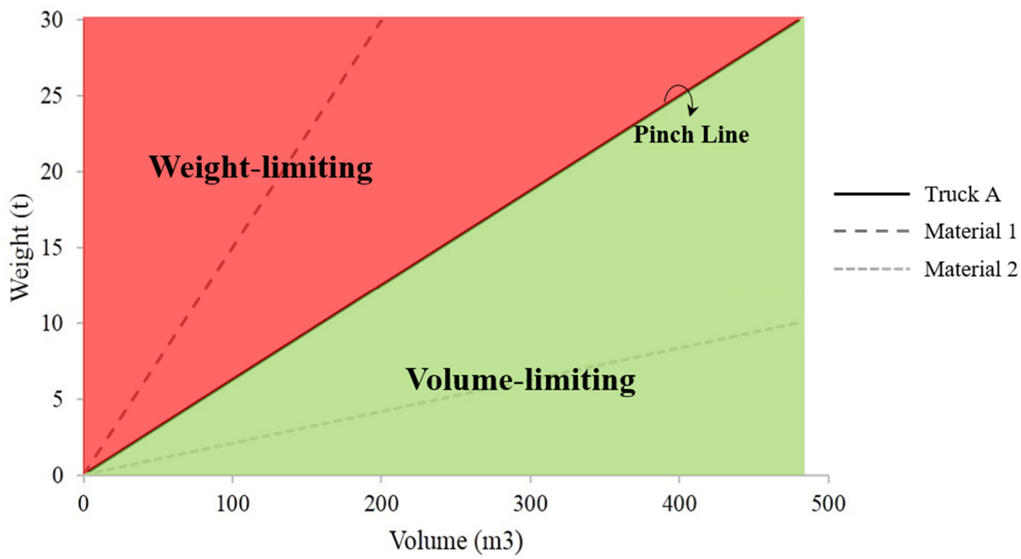

Figure 5.4: Weight-volume graph for vehicles and materials.

If the material has larger bulk density compared to the bulk density of vehicle capacity (gradient ≥ ρ_m (or $\rho_{m'}$)), it is considered as WLM (e.g., material 1 in Figure 5.4). Otherwise, it is considered as VLM (e.g., material 2 in Figure 5.4). In other words, the bulk density of vehicle capacity is noted as pinch line. If the weight-volume line for the transported material is above the pinch, it is a weight-limiting problem; while if it is below the pinch, it is a volume-limiting problem. In some cases, the same transported material can be WLM and VLM for two vehicles respectively, provided that its bulk density is greater than the bulk density of one vehicle and lower than the other. These cases are considered as dual limiting problems. In order to address this issue, special adjustment has to be made. For instance, material 1 is WLM for truck A, at the same time it is VLM for truck B. Thus, in this model, Equations (5.14) and (5.15) are used to determine the C^{Tr} [t/y] for truck A while Equations (5.16) and (5.17) are used to determine the C^{Tr} [t/y] for truck B.

In addition, decision-makers can determine the number of vehicle required by doing manual calculations (see Section 5.4) or by using a correlated graph developed in this paper. Figure 5.5 shows the correlated graph used for weight limiting case and volume limiting case. α_w in the figure refers to the maximum weight of material that the vehicle can carry daily; while α_v refers to the maximum volume of material that the vehicle can carry daily. These diagrams are constructed by using equations below:

$$\alpha_{w_m} = \mathrm{num}_{i,m,j}^{\mathrm{Trip\_Max}} \times \mathrm{Cap}_m^{\mathrm{Weight}} \tag{5.36}$$

$$\alpha_{v_m} = \mathrm{num}_{i,m,j}^{\mathrm{Trip\_Max}} \times \mathrm{Cap}_m^{\mathrm{Volume}} \tag{5.37}$$

The number of the respective vehicle required can be easily calculated by dividing the total weight of WLM delivered per day by α_w, or dividing the total volume of VLM delivered per day to α_v. Note that the number should be rounded-up to the nearest larger integer. For instance, from Figure 5.3, truck B is selected to deliver 200 t/d of WLM to a hub which located 60 km away. By using Figure 5.5, α_w is equal to 165 t/d. Hence, the number of vehicle needed for this case will be the nearest larger integer of 200/165, i.e., 2.

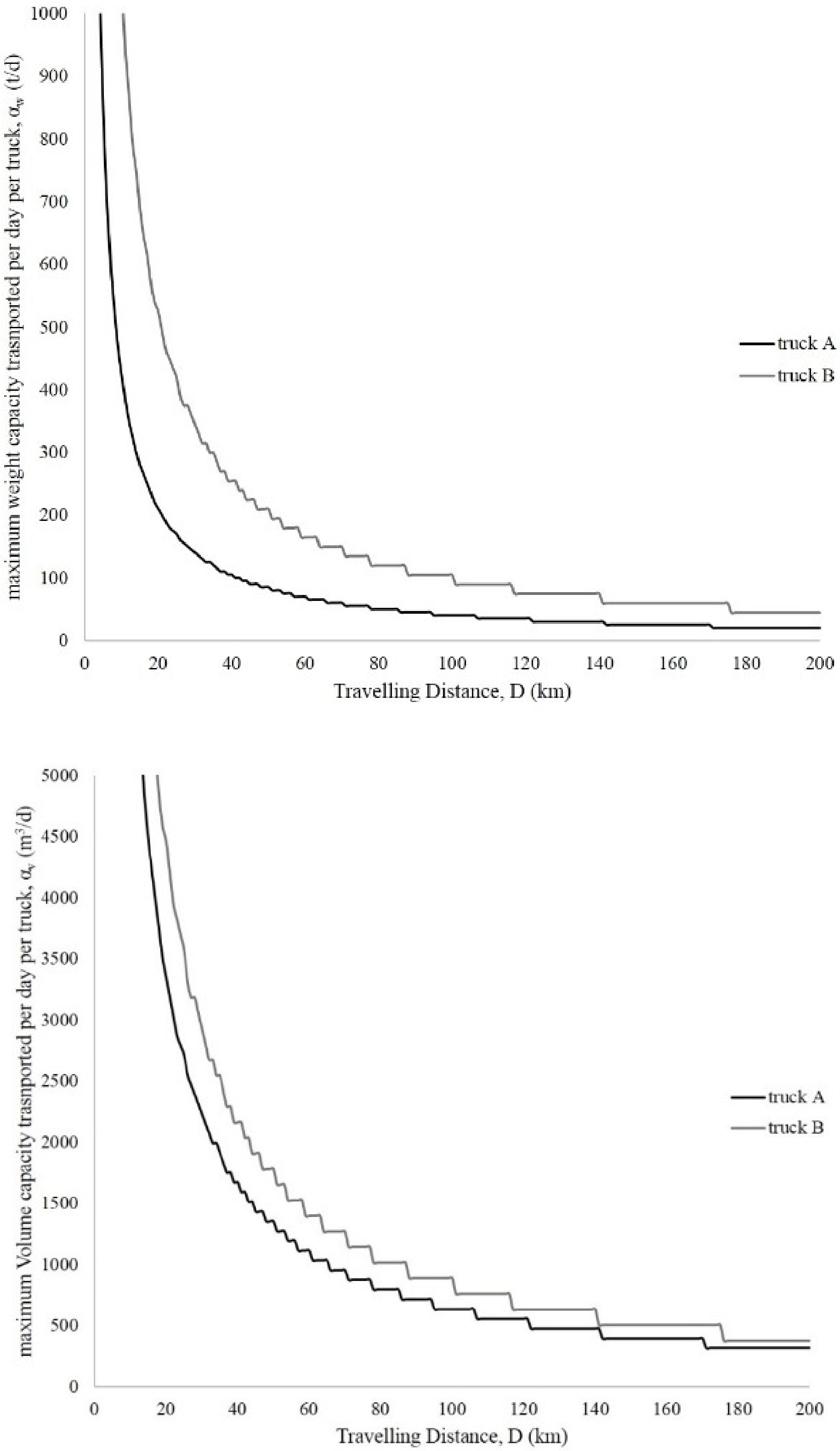

Figure 5.5: Correlated graph to determine number of vehicle for (T) WLM and (B) VLM.

5.5.2 User manual for SVS diagrams

Figure 5.6 shows the step-by-step user manual of using the proposed decision-making tools.

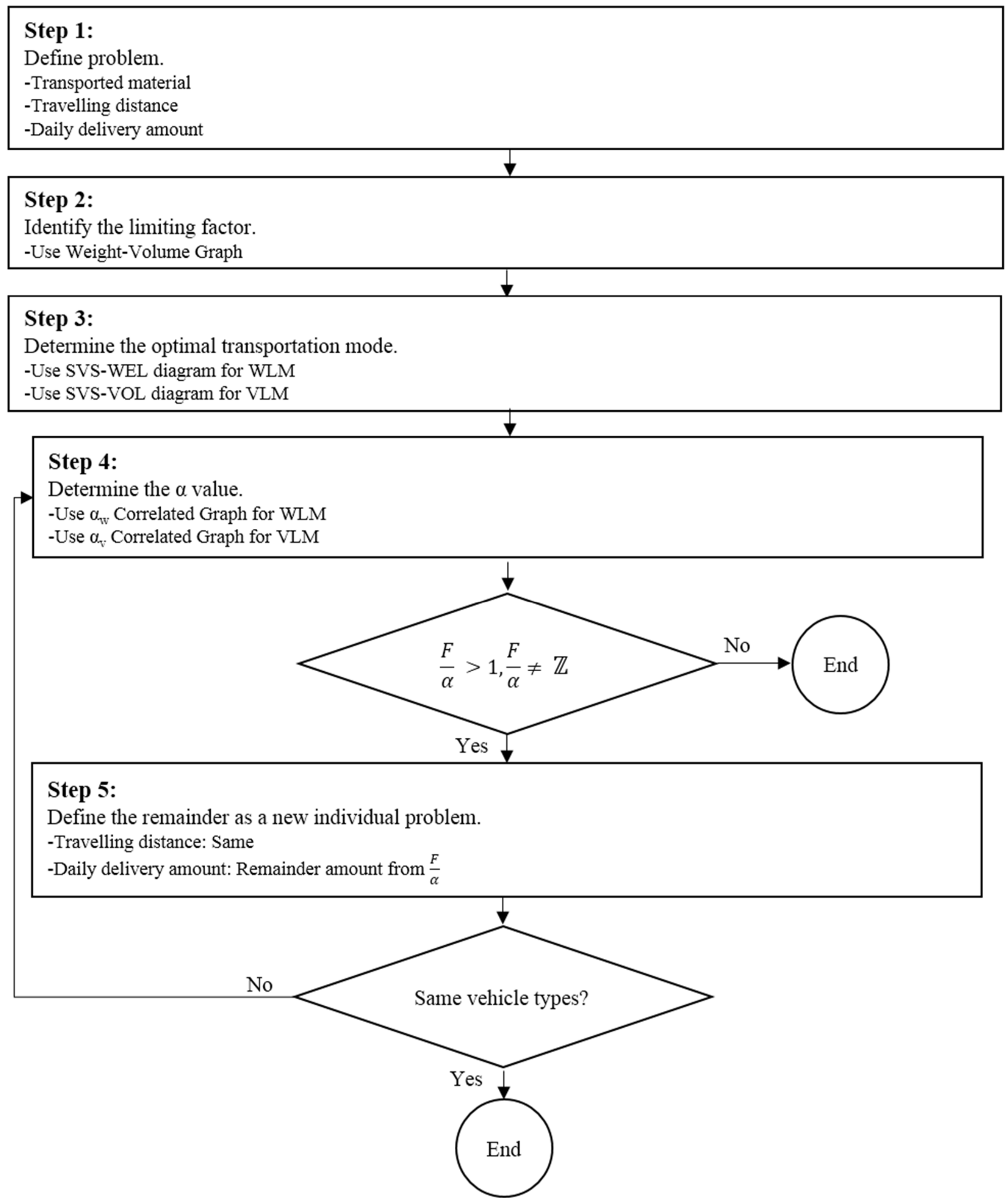

Figure 5.6: User manual for the proposed SVS diagrams.

Firstly, user has to define the problem, i.e., (i) which material need is delivered; (ii) how much is the daily delivered amount; and (iii) how far is the delivering distance. Other than these 3 points, user might also need to identify the amount of transportation resources available in market. However, this issue is not considered in this work (see Assumption 2). Next, user has to identify whether the transported materials are WLM or VLM by using the aforementioned Weight-volume graph. If it is WLM, SVS-WEL diagram is used to determine the optimal transportation mode in the next step; else, SVS-VOL diagram is used.

However, the SVS diagrams will always provide a solution that will only utilise a single type of vehicle. This might not be optimal for some cases. For instance, in the same example mentioned previously (i.e., 200 t/d of WLM is delivered to a hub which located 60 km away), we already know that two truck B are needed. Since α_w is 165 t/d, this indicates that the second truck will only carry 35 t/d of the material. According to SVS-WEL diagram, the best transportation mode for transporting 35 t/d of WLM to the 60 km hub is actually truck A. Thus, the optimal solution for this example will be one truck A and one truck B instead of merely using two truck B. In order to address this problem, the following steps should be carried out:

I. Identify the limiting factor by using Weight-volume graph (see Figure 5.4).

II. Determine the optimal transportation mode from SVS diagram (see Figure 5.3).

III. Determine α value of the selected truck by using the correlated graph (see Figure 5.5).

IV. Divide the daily delivered amount to α value. If the resulting value is less than 1 or equal to a whole number, the problem is considered solved (e.g., 200/165 is a decimal number that is larger than 1, the problem is not considered solved).

V. Else, a new individual problem is defined by using the same travelling distance, but the daily delivery amount is now changed to the remainder value from the division (e.g., the remainder of 200/165 is 35).

VI. SVS diagram is used again to identify the optimal transportation mode for this new problem. If the same transportation mode is selected, the problem is considered solved. Only mono-transportation mode is optimal for this problem.

VII. Else, multi-transportation mode (more than 1 type of vehicle is used) is optimal for this problem. Steps II to V are repeated until division result is less than 1 (or equal to a whole number) in step III; or same transportation mode is obtained from step V.

With the listed steps, the restriction of using only mono-transportation mode does no longer exist. In fact, after following these steps, the optimal solution for the aforementioned example will be one truck A and one truck B instead of two truck B. In other words, the obtained solution is improved.

5.6 Case Study Description

The same case study in Johor state which presented in Chapter 4 is extended in this work. The additional information is tabulated in the following subsections:

5.6.1 Biomass availability in Johor

The biomass availability of Johor state has been presented in Chapter 4 (refer to Section 4.3.1).

5.6.2 Conversion technologies in processing hub

The description of all the biomass conversion technologies considered in this case study has been presented in Chapter 4 (refer to Section 4.3.2).

5.6.3 Potential processing hubs

Chapter 4 has concluded that there are 25 potential locations which are suitable to set up processing hub (see Figure 4.16).

5.6.4 Transportation modes

Five types of trucks (m_1, m5$_2$, m_3, m_4 and m_5) are considered in this work. Note that m_5 refers to the jumbo tube trailer which only been used to deliver gaseous products. The dimensions and the weight limit of each truck are stated in Table 5.1 while the operating conditions of each truck is tabulated in Table 5.2.

5.6.5 Economic data

The material cost and technology investment cost are tabulated in Chapter 4 (see Table 4.4 and Table 4.5). Other transportation-related expenses are given in Table 5.3 while the economic data required to determine the carbon penalty is written in Figure 5.4.

Table 5.1: Dimension of each transportation mode and its weight-limit.

Vehicle	Length [m]	Width [m]	Height [m]	Weight Limit [t]
m_1	5.02	2.13	2.13	5.00
m_2	6.00	2.40	2.13	10.00
m_3	12.00	2.40	1.50	20.00
m_4	13.62	2.48	2.70	32.00
m_5	11.30	2.40	3.20	4000 [m^3]

Table 5.2: Other operating specification of trucks.

Vehicle	Sp^{Max} [km/h]	Sp^{Min} [km/h]	DT [h]	$rate_m^{Fuel}$ [L/km]	LS^{Tr}[y]
m_1	70	50	0.33	0.213	10
m_2	70	50	0.67	0.213	10
m_3	70	50	1.00	0.235	10
m_4	70	50	1.33	0.235	10
m_5	70	50	0.33	0.261	10

Table 5.3: Transportation-related expenses.

Vehicle	C_m^{Proc} [RM]	C^{Repair} [RM/km]	C^{Fuel} [RM/L]	HW [RM/h]
m_1	70,000	0.18	1.90	10
m_2	90,000	0.22	1.90	10
m_3	125,000	0.34	1.90	10
m_4	150,000	0.45	1.90	10
m_5	170,000	0.45	1.90	10

Table 5.4: Economic data for carbon emission penalty.

Item	Cost [RM/m^2]
C^{Fuel_Plantt}	5.00
C^{Fert}	0.10
$C^{Utility\_Plantt}$	0.30
C^{Labour_Plantt}	3.40

5.6.6 Environmental assessment

Transportation process is the main CF contributors in the supply chain. The CO_2 emission rate of each vehicle is tabulated in Table 5.5 while other parameters used are given in Table 5.6.

5.7 Sensitivity Analysis

Sensitivity analysis is conducted to analyse the effect of the five realistic factors, including terrain profile, traffic congestion, fuel price fluctuation and individual environmental preference. These factors are selected based on its actual condition which will cause variation on some of the assumed parameters (e.g., fuel consumption rate, average driving speed, etc.). Other parameters such as vehicles capacity constraints are not chosen since they are less likely to be fluctuated (e.g., unless utilised different types of vehicle which will change the entire case study background; else it is very unlikely to change the design of the existing vehicles). Their descriptions are given in the subsections below accordingly while the sensitivity studies of these factors are discussed in Section 5.8. Figure 5.7 shows the step-by-step approach for the sensitivity analysis.

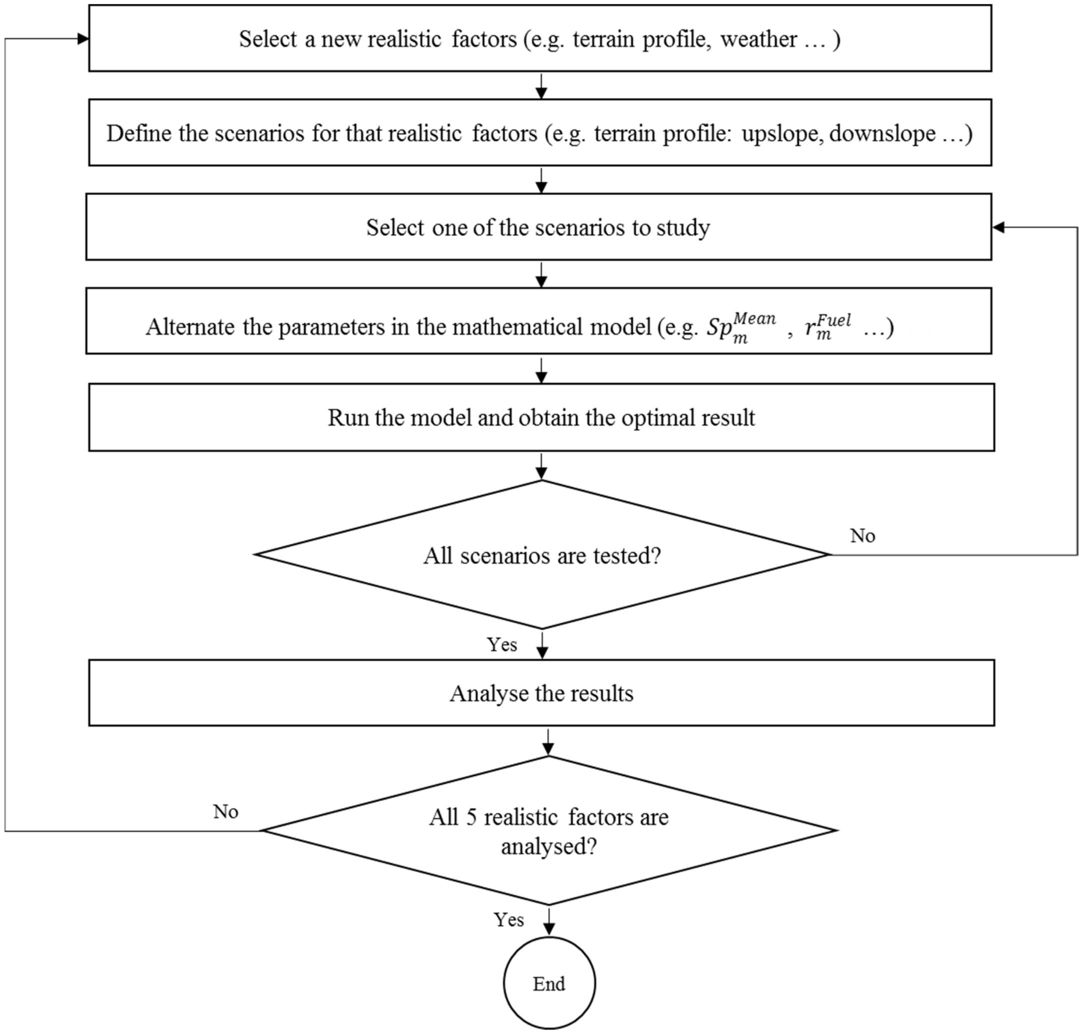

Figure 5.7: Step-by-step approach for sensitivity analysis.

Table 5.5: CO_2 emission rate of each vehicle.

Vehicle	**$frac_m^{CO_2}$ [gCO$_2$/km]**
m_1	553.8
m_2	553.8
m_3	611.0
m_4	611.0
m_5	678.6

Table 5.6: Fraction of CO_2 absorbed by ocean, CO_2 absorption rate and life span of forest.

Parameter	Value	Reference
$\mathbf{frac}^{\mathbf{ab\_Ocean}}$ [%]	25	(Farrelly et al., 2013)
$\mathbf{Abs}^{\mathbf{CO_2}}$ [kgCO_2/(m^2.y)]	1.12	(Zhou et al., 2015)
$\mathbf{LS}^{\mathbf{Plantt}}$ [y]	30	-

5.7.1 Terrain profile

Terrain profile or elevation profile is a two-dimensional cross-sectional view of the landscape between two locations on a topographic map. It plays a very crucial role in the fuel consumption rate of vehicles (Franzese & Davidson, 2011). In this work, terrains are categorised into five classes, i.e., flat terrain, mild downslope terrain, mild upslope terrain, severe downslope terrain and severe upslope terrain. The characteristic of each terrain and the fuel consumption rate for each case are tabulated in Table 5.7. Generally, vehicle consumed more fuel when passing an upslope terrain compared to a downslope terrain. In order to obtain the new optimal result for each scenario, the new estimated value of $\mathrm{rate}_m^{\mathrm{Fuel}}$ (or $\mathrm{rate}_{m'}^{\mathrm{Fuel}}$) [L/km] is used in Equation (5.26).

5.7.2 Weather change

Similar to other Southeast Asia (SEA) countries, Malaysia does not have four season climates. Instead, Malaysia experiences dry season (June to September) and rainy season (December to March). The rainy season is usually caused by the monsoon wind, which carries high moisture content. Based on the severity of the rainstorm, it is classified into mild rainfall and severe rainfall. Due to safety reason, the driving speed under rain should be lowered, thus this will lead to a longer delivery lead-time. The estimated driving speed for each vehicle during dry season and rainy season are given in Table 5.8. These new $\mathrm{Sp}_{m}^{\mathrm{Mean}}$ (or $\mathrm{Sp}_{m'}^{\mathrm{Mean}}$) [km/h] value is substituted into both Equations (5.12) and (5.13) in order to obtain the new optimal results.

Table 5.7: Characteristic of terrain and the fuel consumption rate of each vehicle.

Terrain	Road grade	$\mathrm{rate}_{m}^{\mathrm{Fuel}}$ [L/km]				
		m_1	m_2	m_3	m_4	m_5
Severe downslope	< -4 %	0.071	0.071	0.078	0.078	0.087
Mild downslope	-4 % to -1 %	0.104	0.104	0.114	0.114	0.127
Flat	-1 % to +1 %	0.213	0.213	0.235	0.235	0.261
Mild upslope	+1 % to +4 %	0.354	0.354	0.392	0.392	0.435
Severe upslope	> +4 %	0.899	0.899	0.991	0.991	1.101

Table 5.8: Driving speed during dry season and rainy season.

Road grade	$\mathrm{Sp}_{m}^{\mathrm{Mean}}$ [km/h]
Dry	60
Rainy (mild)	50
Rainy (severe)	40

5.7.3 Traffic congestion

Traffic congestion or traffic jam is a condition on road networks that occurs when road supply does not meet the demand (Almselati et al., 2011). In Malaysia, traffic congestion is a major problem that creates bottleneck for the business movement in the urban areas. The estimated driving speed for each vehicle under different traffic conditions are listed in Table 5.9. Similar to the Section 5.7.2, the new $\mathrm{Sp}_{m}^{\mathrm{Mean}}$ (or $\mathrm{Sp}_{m'}^{\mathrm{Mean}}$) [km/h] value is substituted into both Equations (5.12) and (5.13).

Table 5.9: Driving speed during different traffic conditions.

Traffic Condition	$\mathrm{Sp}_{m}^{\mathrm{Mean}}$ [km/h]
Dry	60
Rainy (mild)	40
Rainy (severe)	25

5.7.4 Fuel price fluctuation

Fuel price is fluctuating throughout the year, driven by the increasing global demand, limited supply of fuel and regional political instability. This price changes might affect the decision-making in SCM as the optimal choice of vehicle might change. Figure 5.8 shows the recent diesel price fluctuation in Malaysia. The new value of $\mathrm{C}^{\mathrm{Fuel}}$ [RM/L] is substituted into Equation (5.26) to obtain the new optimal solution.

5.7.5 Environmental preference

Carbon emission penalty is determined by using the quantifying approach proposed by Zhou et al. (2015). However, the magnitude of the penalty is free to be adjusted depend on the company's business policy and the local regulation. For instance, decision-makers can set a higher penalty cost in the model, indicating that they are willing to run their business in a more sustainable way. In order to do that, the new estimated $C^{\text{Penalty\_CO}_2}$ [RM/y] is substituted into Equation (5.33). The sensitivity of carbon pricing to the decision made will be discussed in Section 5.8.

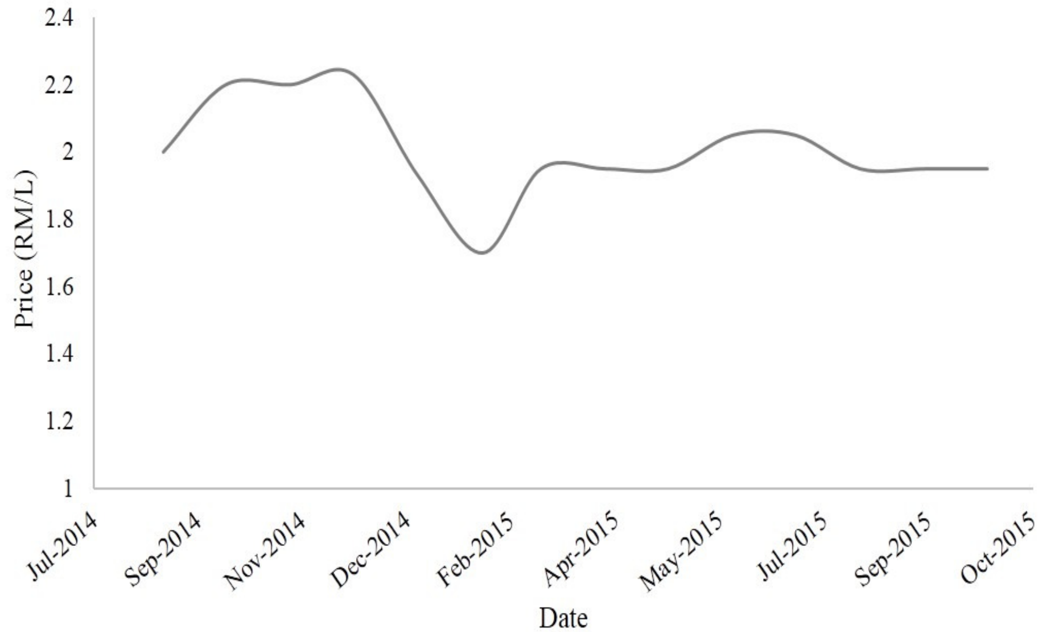

Figure 5.8: Diesel price in Malaysia (Data source: (Energypedia, 2014)).

5.8 Result and Discussion

The results and discussions are given in the following subsections:

5.8.1 Limiting factor identification

The bulk density of each material (i.e., biomass and final product) is given in Table 5.10. By using these data, the weight to volume profile is constructed (see Figure 5.9). Since m_5 is used exclusively for the transportation of gaseous product, it is not presented in Figure 5.9. It is clearly seen that citric acid, bio-oil, animal feed, bio-ethanol, energy pack, sugarcane bagasse, PKS are considered as WLM for m_1, m_2, m_3, and m_4; while paddy straw and DLF are considered as VLM for m_1, m_2, m_3, and m_4. However, it is slightly complicated for other materials. For instance, rice husk is considered as WLM for m_1, m_2, and m_4, but VLM for m_3; EFB and pineapple peel are considered as WLM for m_1 and m_2, but VLM for m_3 and m_4; while bio-char is considered as WLM for m_1, but VLM for m_2, m_3, and m_4. These are known as dual limiting problems.

Table 5.10: Bulk density of biomass.

Material	Bulk density [t/m^3]	Reference
EFB	0.355	(Tan et al., 2014)
PKS	0.560	(Fono-Tamo & Koya, 2013)
Sugarcane bagasse	0.603	(Gómez et al., 2012)
Pineapple waste	0.350	(Babel et al., 2004)
Rice husk	0.380	(Zhang et al., 2012)
Paddy straw	0.194	(Zhang et al., 2012)
DLF	0.200	-
Animal feed	0.960	(HAPMAN Global, 2016)
Bio-char	0.320	(Brewer & Levine, 2015)
Energy pack	0.840	-
Citric acid*	1.660	(Apelblat, 2014)
Bio-ethanol*	0.810	(Matuszewska et al., 2013)
Bio-oil*	1.170	(Gansekoele, 2016)

*liquids products are kept in barrel

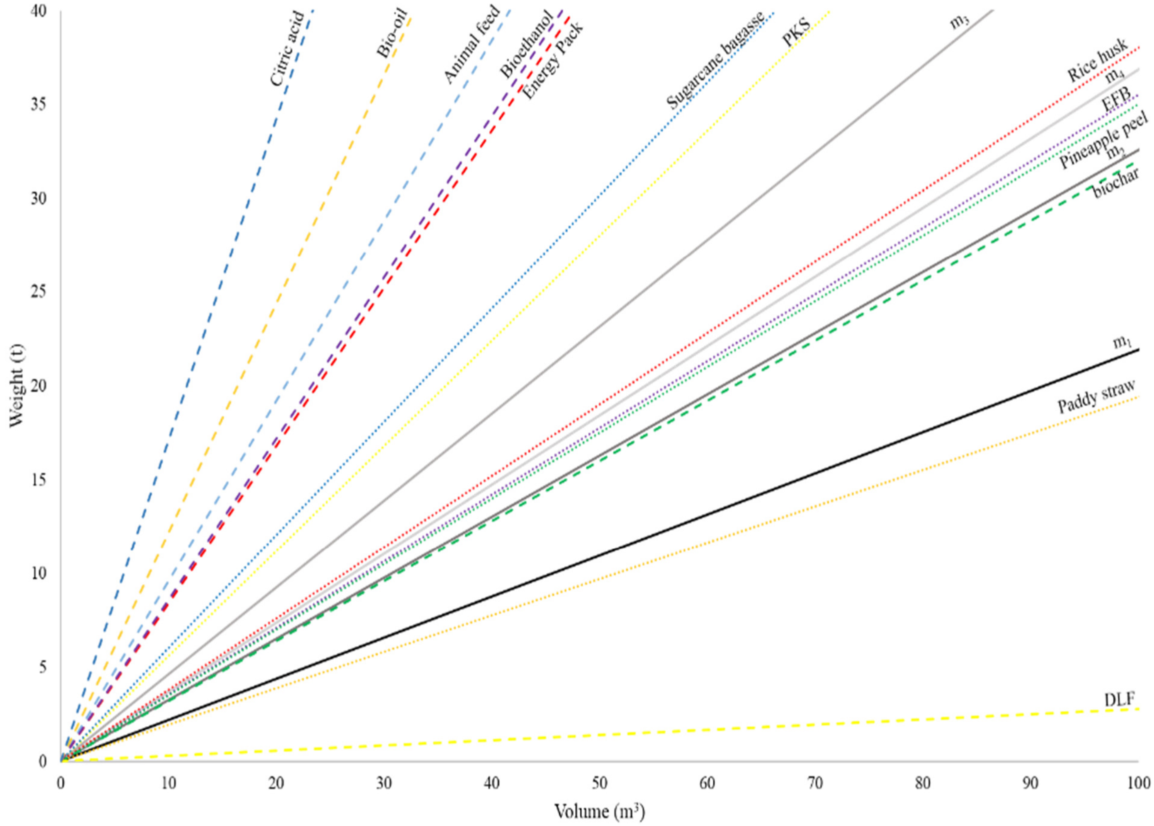

Figure 5.9: Weight-volume profile.

5.8.2 Comparative study

The comparisons between the different settings of these two works (Chapter 4 and Chapter 5) are summarised in Table 5.11. Note that the current study is separated into two cases, where case 1 concerns only single objective (economic performance) while case 2 considers multiple objectives (economic and environmental performances).

Table 5.11: Comparison based on model setting.

Model Setting	Chapter 4 (Previous work)	Chapter 5 (Current work)	
		Case 1	Case 2
Objective functions	Economic	Economic	Economic and Environmental
Vehicle physical constraint	Not considered	Considered	Considered
Vehicle types	Not considered	Considered (5 types)	Considered (5 types)
Transportation cost estimation	Linearised cost function is used	Detailed calculation	Detailed calculation
CO_2 emission penalty	Not considered	Not considered	Considered

In the previous work, the transportation cost of the case study is determined by using a correlated cost constant, C^T [RM/t/km] (see Equation (4.14)). The value of this cost constant is adapted from a Malaysia case study presented in Lam et al. (2013). Despite both works are using a same case study, the transportation cost calculated from both works are different. Figure 5.10 shows that the transportation cost determined in the previous work is much higher than the transportation cost determined in this work. This is not surprising as the linearised transportation cost constant is not capable to represent the realistic of case study. For instance, in the real life, it costs about the same to deliver 0.5 t of WLM and 5 t of WLM to a same location via a same transportation mode. However, by using the linearised cost constant proposed in previous work, the cost required to deliver 5 t of WLM is ten times the cost required to deliver 0.5 t of WLM. With the inaccurate cost estimation, the optimality of the solution obtained is no longer guaranteed. On the other hand, the results shown in the previous work suggest that the transportation cost will decrease as the number of processing hub increases. However, this not in align with the results for the current work. From Figure 5.10, it can be observed that after 5 processing hubs, the increase number for processing hub will no longer reduce the transportation cost.

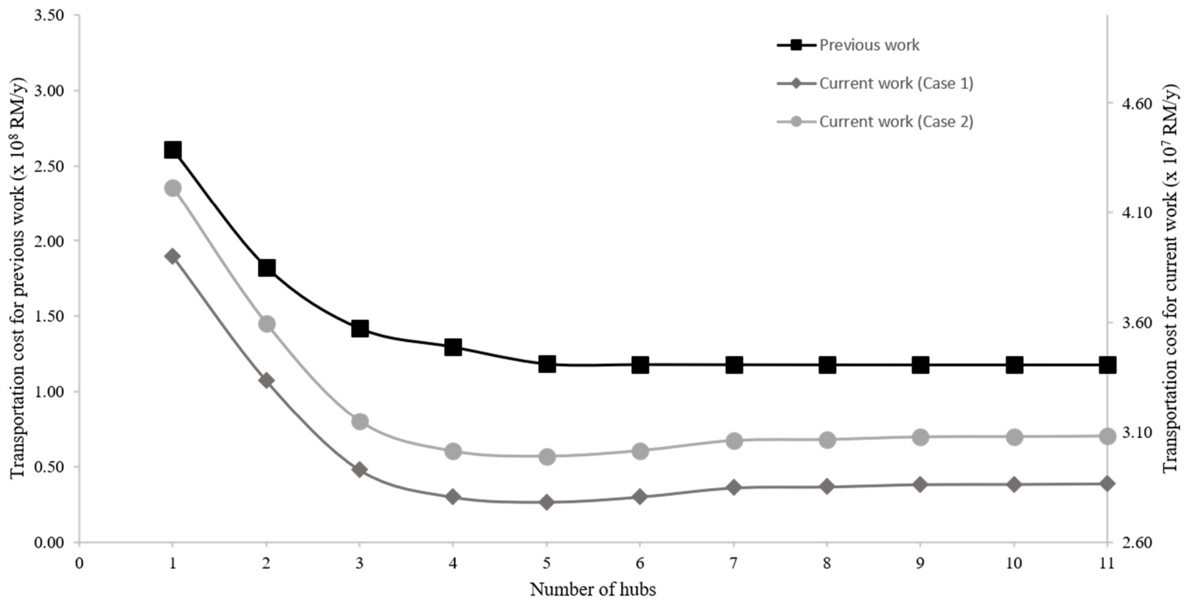

Figure 5.10: Transportation cost estimation in previous work and current work.

In order to have an insight view of this issue, the breakdown of the transportation cost is shown in Figure 5.11. From the figure, it shows that the total CAPEX for transportation, labour cost, mileage and maintenance cost required is reducing along with the number of hub. However, after 3 processing hubs, CAPEX will increase with the increase in number of hub instead. This indicates that the total number of transportation mode required is actually increased. This can be explained by using the following example: 10 ton of raw material R can be converted into 5 ton of product P, while truck T is able to transfer 5 ton of product P in a single trip. Therefore, if 5 ton of product P is produced in a single processing hub, one truck T is sufficient. However, if 5 ton of product P is produced in two separate processing hubs, two trucks is required in total (one truck T is needed for each processing hub in order to complete the delivery).

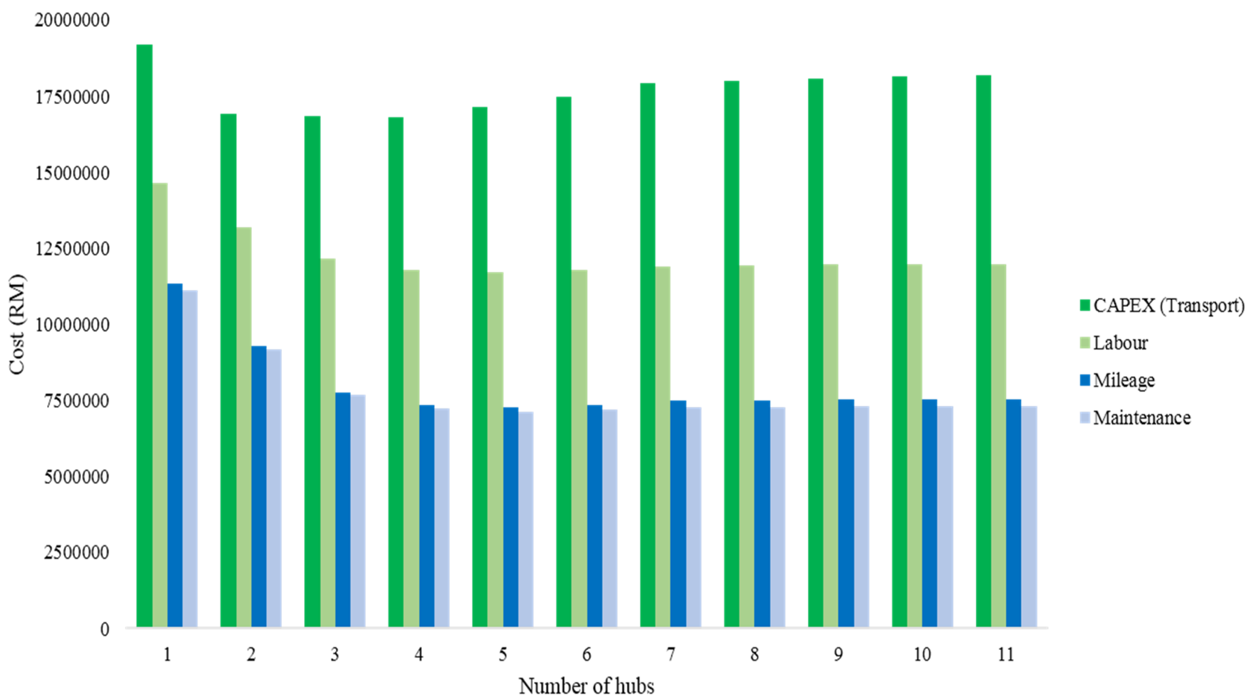

Figure 5.11: Transportation cost distribution for current work.

Figure 5.12 shows the annual net profit that can be obtained with different number of hubs. The results from both works show a similar convex curve pattern. In other words, the net profit will increase with the number of hubs initially, but will decrease after it reached a maximum point. Generally, the increase in number of hubs will cause a higher investment cost but lower the transportation cost simultaneously. The reduction in transportation cost is due to the better biomass allocation (biomass is delivered to a nearer hub). However, the increment in number of hubs becomes unfavourable when the saved cost is not able to compensate for the additional investment cost. Due to the inaccurate cost estimation in the previous work, the optimal number of hubs determined from the previous work (i.e., 5 hubs) is different from the one determined in the current work (i.e., 3 hubs for both cases). This is critical since the result from previous work is misleading the decision-makers, causing an undesirable waste of money. The biomass allocation design for 5 processing hubs (proposed in Chapter 4) is shown in Figure 4.16 while the biomass allocation design for 3 processing hubs is shown in Figure 5.13.

Table 5.12 and Table 5.13 show the comparison on the total expenses for these two proposed designs. The results show that the transportation cost required for 5 processing hubs is 5.2 % (~ RM 1,500,000) lesser than the transportation cost required for 3 processing hubs; while total carbon emission for 5 processing hubs is 7.2 % (~ 800 tCO_2, equivalent to RM240,000 carbon emission penalty) lesser than the CO_2 emitted for 3 processing. However, this reduction cannot compensate the additional hub investment cost and eventually lead to an additional 11.6 % of total expenses (i.e., about RM 4,400,000). Hence, this can be concluded that having a comprehensive estimation for transportation cost (consider the vehicle's capacity constraints) is very vital during the optimisation of supply chain synthesis. On top of that, Table5.14 shows that the optimal transportation mode selection for both cases are exactly same. The sensitivity analysis for the carbon penalty per unit of CO_2 emission is elucidated in Section 5.8.5.

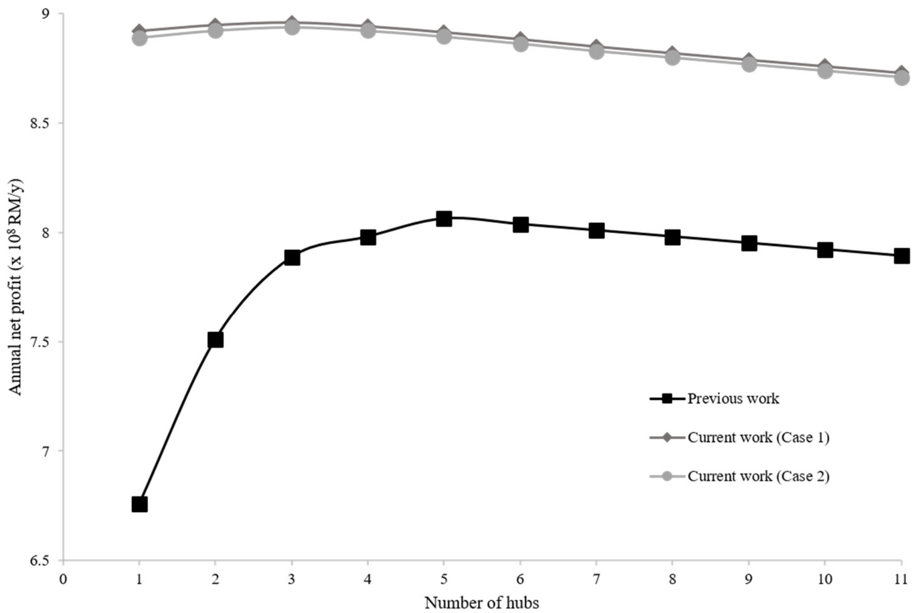

Figure 5.12: Annual net profit estimation in previous work and current work.

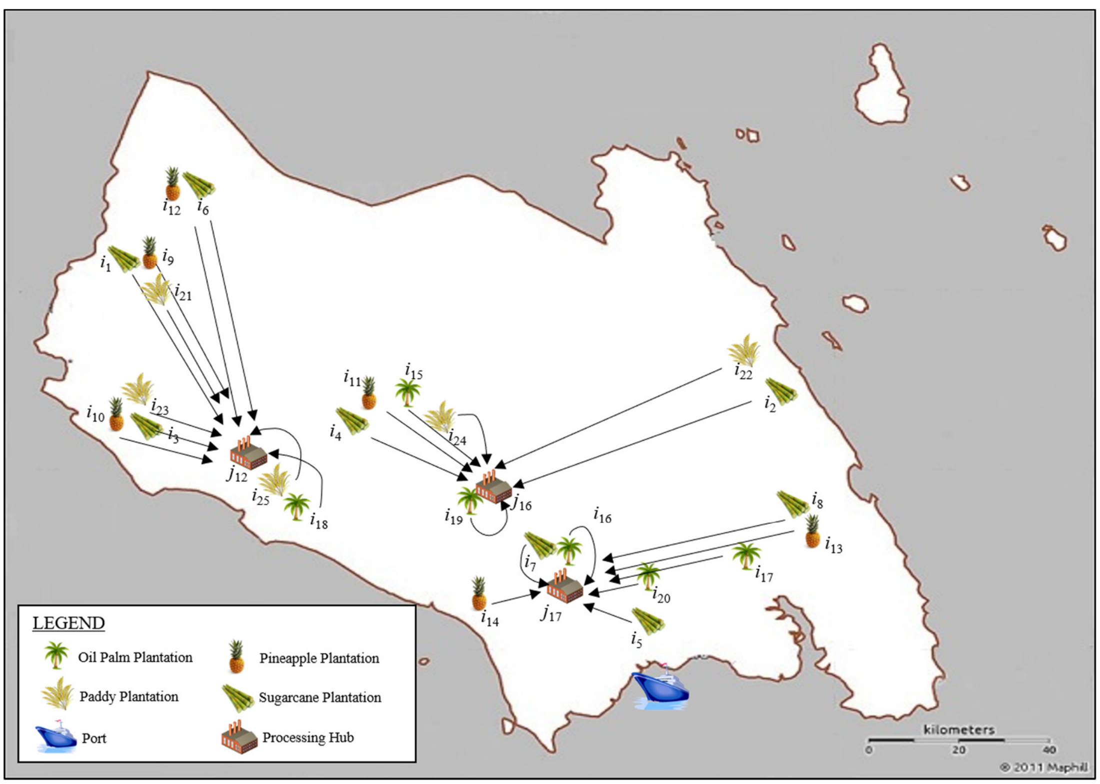

Figure 5.13: Optimal biomass allocation design (Maphill, 2013).

Table 5.12: Total cost and transportation design for 5 processing hubs (Case 1).

Source	Selected hub	Number of vehicle				C^{Tr} [RM/y]	C^{Inv_Hub} [RM/y]
		m_1	m_2	m_3	m_4		
i_1	j_{12}	1	0	0	0	65,724	Estimated investment cost for 5 hubs
i_2	j_{24}	1	0	0	0	69,309	
i_3	j_{12}	0	1	0	0	49,264	
i_4	j_{22}	1	0	0	0	9,995	
i_5	j_{17}	1	0	0	0	28,962	
i_6	j_{12}	1	0	0	0	74,523	
i_7	j_{17}	1	0	0	0	10,386	
i_8	j_{24}	1	0	0	0	9,995	
i_9	j_{12}	1	0	0	0	65,724	
i_{10}	j_{12}	1	0	0	0	43,367	
i_{11}	j_{22}	1	0	0	0	9,995	
i_{12}	j_{12}	1	0	0	0	74,523	
i_{13}	j_{24}	1	0	0	0	9,995	
i_{14}	j_{17}	1	0	0	0	34,307	
i_{15}	j_{22}	0	0	0	8	1,203,199	
i_{16}	j_{17}	0	0	0	7	1,048,088	
i_{17}	j_{24}	0	0	0	3	385,434	
i_{18}	j_{12}	0	0	0	8	1,110,353	
i_{19}	j_{16}	0	0	0	4	513,912	
i_{20}	j_{17}	0	0	0	7	1,279,365	
i_{21}	j_{12}	0	1	0	0	72,595	
i_{22}	j_{24}	0	1	0	0	76,336	
i_{23}	j_{12}	1	0	0	0	43,367	
i_{24}	j_{22}	1	0	0	0	999,5	
i_{25}	j_{12}	1	0	0	0	9,995	

Table 5.12 (cont'): Total cost and transportation design for 5 processing hubs (Case 1).

Hub	Demand	Number of vehicle					C^{Tr} [RM/y]	C^{Inv_Hub} [RM/y]
		m1	m2	m3	m4	m5		
j_{12}	Port	0	0	2	17	1	5,991,426	Estimated investment cost for 5 hubs
j_{16}		0	0	0	6	1	2,472,148	
j_{17}		0	0	0	14	1	4,747,769	
j_{22}		0	1	0	18	1	7,026,300	
j_{24}		0	0	0	4	1	1,128,807	
Total		16	4	2	95	5	27,675,159	14,682,455
Total expenses [RM/y] =							42,357,614	
CF^{Total} [m^2/(t/y)] =							14.33	

Table 5.13: Total cost and transportation design for 3 processing hubs (Case 1).

Source	Selected hub	Number of vehicle				C^{Tr} [RM/y]	C^{Inv_Hub} [RM/y]
		m1	m2	m3	m4		
i_1	j_{12}	1	0	0	0	65,724	Estimated investment cost for 3 hubs
i_2	j_{16}	1	0	0	0	79,738	
i_3	j_{12}	0	1	0	0	49,264	
i_4	j_{16}	1	0	0	0	24,334	
i_5	j_{17}	1	0	0	0	28,962	
i_6	j_{12}	1	0	0	0	74,523	
i_7	j_{17}	1	0	0	0	10,386	
i_8	j_{17}	1	0	0	0	37,566	
i_9	j_{12}	1	0	0	0	65,724	
i_{10}	j_{12}	1	0	0	0	43,367	
i_{11}	j_{16}	1	0	0	0	24,334	
i_{12}	j_{12}	1	0	0	0	74,523	
i_{13}	j_{17}	1	0	0	0	37,566	
i_{14}	j_{17}	1	0	0	0	34,307	
i_{15}	j_{16}	0	0	0	12	3,280,249	

Table 5.13 (cont'): Total cost and transportation design for 3 processing hubs (Case 1).

Source	Selected hub	Number of vehicle					C^{Tr} [RM/y]	$C^{\mathrm{Inv\_Hub}}$ [RM/y]
		m1	m2	m3	m4	m5		
i_{16}	j_{17}	0	0	0	7	-	1,048,087	Estimated investment cost for 3 hubs
i_{17}	j_{17}	1	0	0	5	-	1,624,622	
i_{18}	j_{12}	0	0	0	8	-	1,110,353	
i_{19}	j_{16}	0	0	0	4	-	513,912	
i_{20}	j_{17}	0	0	0	7	-	1,279,365	
i_{21}	j_{12}	0	1	0	0	-	72,595	
i_{22}	j_{16}	0	1	0	0	-	87,219	
i_{23}	j_{12}	1	0	0	0	-	43,367	
i_{24}	j_{16}	1	0	0	0	-	24,334	
i_{25}	j_{12}	1	0	0	0	-	9,995	
Hub	**Demand**							
j_{12}	Port	0	0	1	17	1	5,991,426	
j_{16}	Port	0	0	0	20	1	7,609,296	
j_{17}	Port	0	0	0	17	1	5,850,769	
Total		17	3	2	96	3	29,195,910	8,809,470
Total expenses [RM/y] =							38,005,380	
CF^{Total} [m^2/(t/y)] =							15.40	

Table 5.14: Selection of transportation mode for 3 processing hubs.

Case	Number of vehicle				
	m1	m2	m3	m4	m5
1	20	3	1	97	3
2	20	3	1	97	3

5.8.3 SVS diagrams

Figure 5.14 and Figure 5.15 are SVS diagrams constructed for this case study. With the aid of Lingo and Excel, these diagrams are generated within a short period of time (~20 min). From the figures, it is clearly seen that the selection of transportation mode is dependent on the travelling distance and the daily delivery amount. In general, vehicles with greater storage capacity is more suitable to deliver large amount of material to a considerably far destination (lower $C^{\mathrm{Tr\_OPEX}}$); while vehicles with less storage capacity is more favourable to deliver small amount of material to a relatively near destination (lower $C^{\mathrm{Tr\_CAPEX}}$). However, this is not always true. For instance, m_4 is favourable to deliver 250 m^3/d of VLM to a hub which located 50 km away from the source, but if the amount of VLM increased to 252 m^3/d, m_2 which has a relatively low storage capacity become the most favourable option (deliver to the same hub). This is because, the saved $C^{\mathrm{Tr\_OPEX}}$ by using m_4 is no longer able to overcome its high $C^{\mathrm{Tr\_CAPEX}}$ (since higher amount of m_4 is required to delivered 252 m^3/d of VLM). This indicates the non-linearity of the proposed transportation problem.

It is worth noting that Figure 5.14 is only valid for material that has a bulk density greater than 0.463 t/m^3; while Figure 5.15 is only valid for material that has a bulk density smaller than 0.219 t/m^3. If the transported material has a bulk density in between 0.463 t/m^3 and 0.219 t/m^3, the vehicle selection problem will be considered as a dual limiting problem. Therefore, the SVS-WEL and SVS-VOL diagrams constructed in this study are not capable to be used for these materials. Figure 5.16 and Figure 5,17 are α_w and α_v correlated graphs generated from this case study. Both are used to determine the number of vehicle required (see Section 5.5.1).

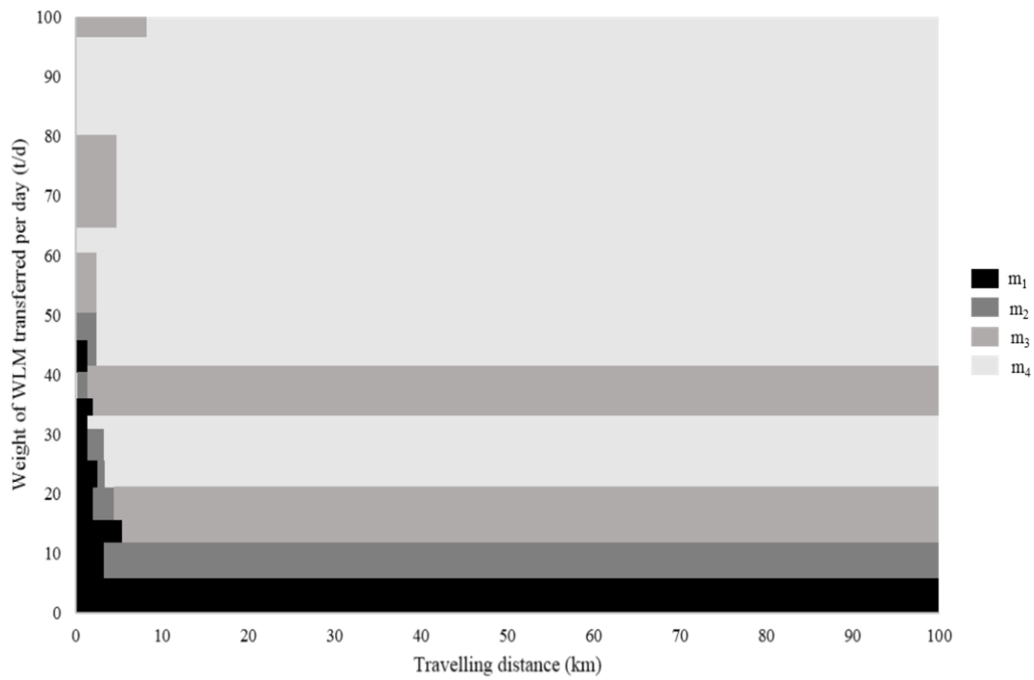

Figure 5.14: SVS-WEL diagram.

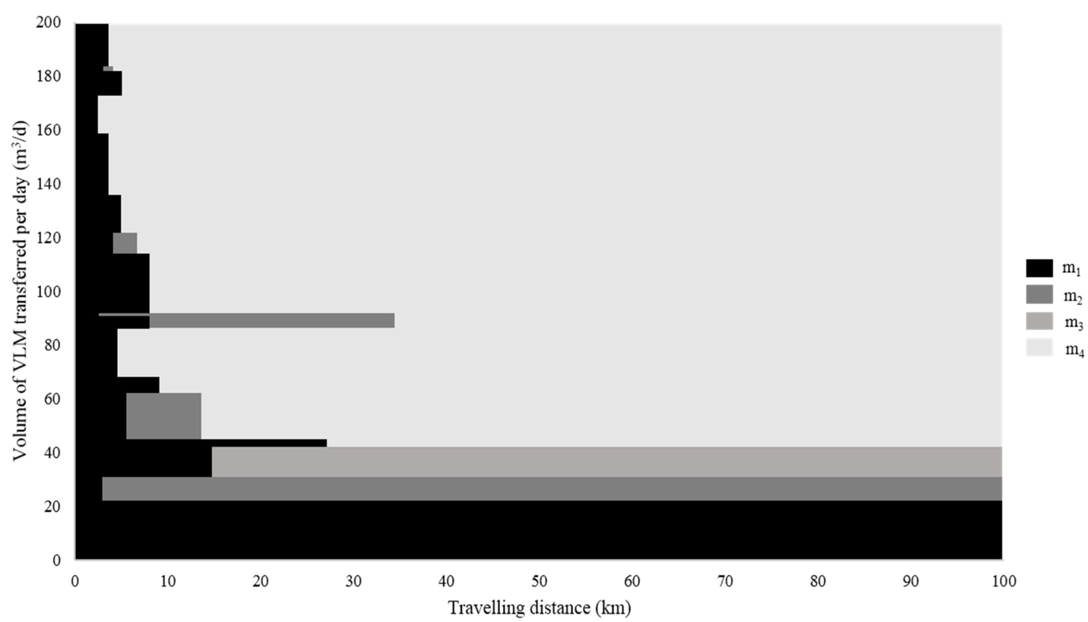

Figure 5.15: SVS-VOL diagram.

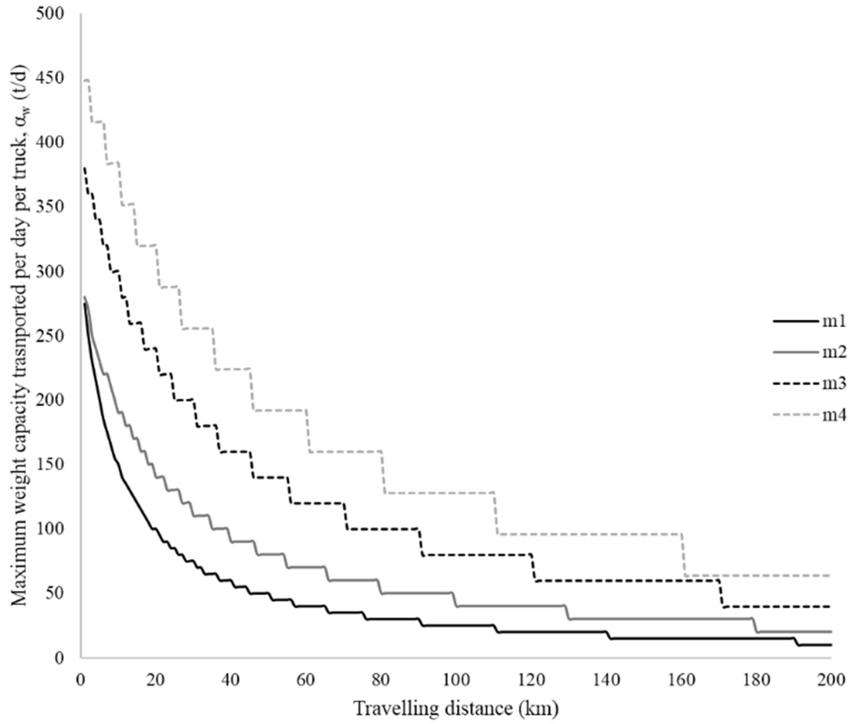

Figure 5.16: α_w correlated graph.

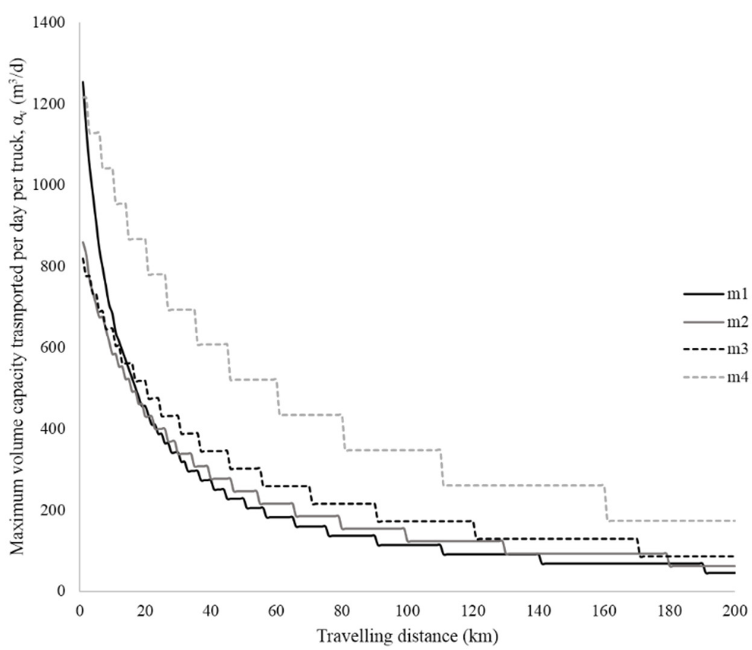

Figure 5.17: α_v correlated graph.

5.8.4 Cost-profile for SVS diagrams

SVS diagrams is a graphical transportation decision-making tool that help decision-makers to select appropriate transportation mode for a specific case. However, the economic data is hidden from these diagrams. Therefore, a cost-profile diagram for each SVS diagram is developed in this subsection (see Figure 5.18 and Figure 5.19). These diagrams tabulate the transportation cost required for each case which defined by (i) amount of material to be delivered and (ii) travelling distance. The relationship between the transportation cost, travelling distance and delivered amount is visualised in these diagrams. With the aid of these diagrams, decision-makers from different stages can analyse the economic viability of the transportation problem easily.

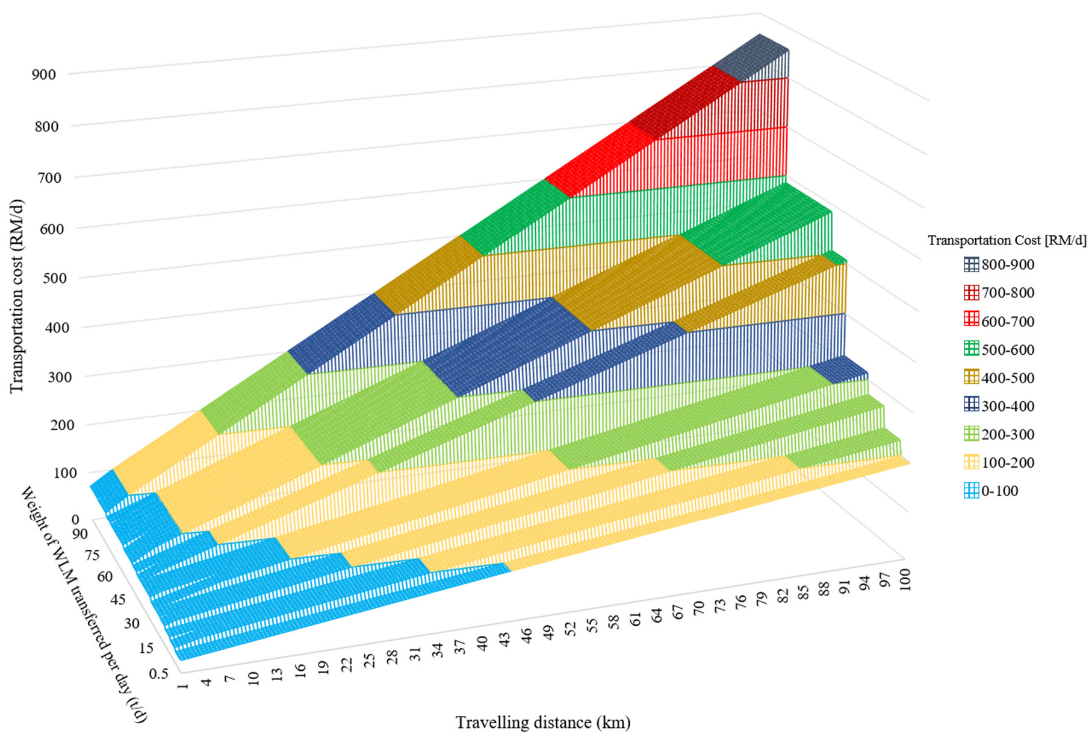

Figure 5.18: Cost-profile for SVS-WEL diagram.

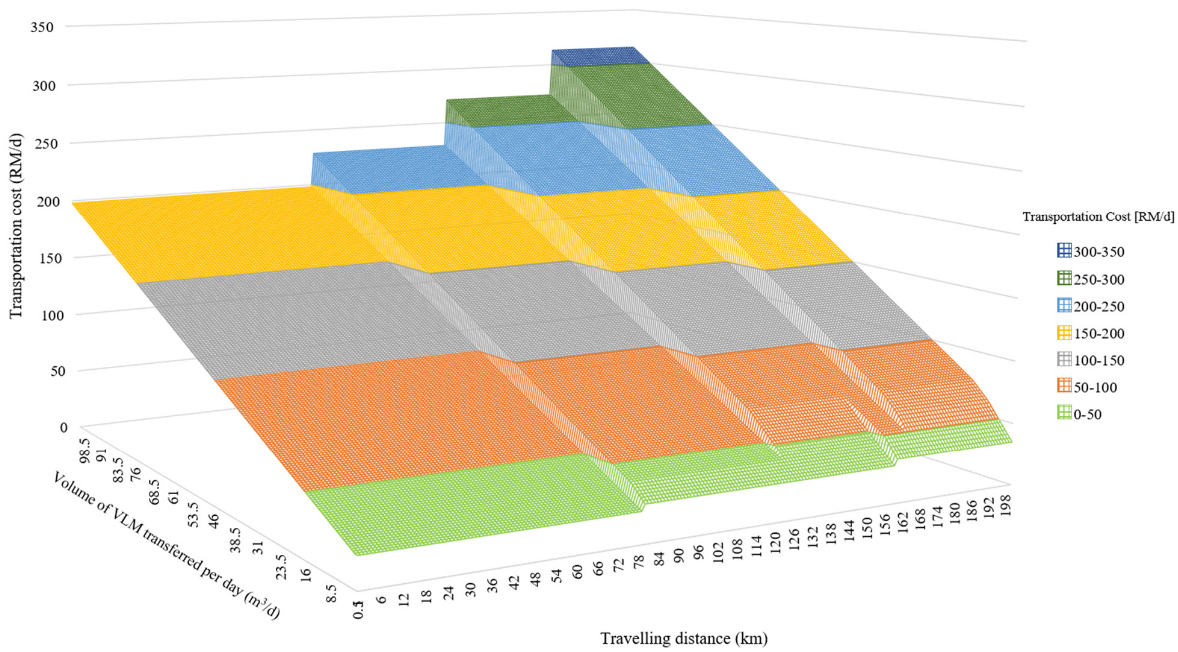

Figure 5.19: Cost-profile for SVS-VOL diagram.

For instance, from the perspective of the industry players, these diagrams can help them to select the most suitable logistics company (minimal and reasonable logistics cost) for their specific cases. First, decision-makers can identify the optimum transportation mode by using SVS diagrams (Figure 5.14 and Figure 5.15) based on the delivered amount and the travelling distance of their specific case. This information can be used for logistic companies screening (i.e., identify which company provides delivery service for that transportation mode). Then, decision-makers can determine the respective estimated transportation cost with the aid of Figure 5.18 and Figure 5.19. This cost data is used as a guideline for the decision-makers to choose the most suitable logistics company (providing the most reasonable offer). To illustrate, assuming 100 m^3 of VLM should be delivered to a location which located 20 km apart. By using Figure 5.15, it can be found that transportation mode m_4 is the optimal transportation mode which lead to minimal transportation cost. According to Table 5.15, Company A is screened-out since it does not provide delivery service for transportation mode m_4. Note that Company A should still be considered is it provide lower charges compared to other companies). From Figure 5.19, it is found that the estimated logistics cost is around RM72.26. Both Company B and Company C provide reasonable offer (i.e., within 25 % margin, this threshold value can be varied depending on the decision-makers). At the same time, based on other company profile analysis, Company C with good reputation is more likely to be selected despite Company B provides lower charges.

Table 5.15: Logistics companies' data.

Logistics Company	**m_4**	**Charges [RM/trip]**	**Remarks**
A	No	120.0	Good Reputation
B	Yes	86.4	Bad Reputation
C	Yes	90.0	Good Reputation

From the drivers' perspective (or logistics companies' perspective), these diagrams can be the guideline to maximise their possible income by having a correct business strategy. To illustrate, the four scenarios presented in Table 5.16 is used. Note that in scenario I and scenario III, 15 t of WLM is required to be delivered to a customer which located 15 km apart and 60 km apart respectively; while in scenario II and scenario IV, 60 t of WLM is required to be delivered to a customer which located 15 km apart and 60 km respectively. By using Figure 5.18, the estimated logistics cost can be extracted from Figure 5.18 (see Table 5.15). By assuming a 25 % margin of the logistics company, the maximal profit of each scenario can now be determined by multiplying the obtained estimated logistics cost (obtained from Figure 5.18) to the assumed margin and the maximum amount of customer to be served per day (values obtained by dividing maximal number of trips per day to the number of trip required per delivery). As a result, decision-makers might prefer scenario IV (i.e., large-capacity and long-distance delivery), as the maximal possible profit that can be obtained is significantly higher than other scenarios. In short, these cost-profile diagrams can be served as an alternative decision-making tool to help decision-makers from different stages in making appropriate decisions.

Table 5.16: Two delivery scenarios.

Scenario	Distance [km]	Capacity [t]	Cost[a] [RM/trip]	$\mathrm{num}_{i,m,j}^{\mathrm{Trip\_Max}}$ [b] [trip/d]	$num_{i,m,j}^{\mathrm{Trip}}$ [b] [trip]	Profit[c] [RM/d]
I	15	15	62.49	13	1	203.09
II	15	60	137.88	10	2	172.35
III	60	15	150.45	6	1	225.68
IV	60	60	374.74	6	2	281.06

[a] Estimated logistics cost obtained from Figure 5.18.
[b] Obtained from Figure 5.16 based on Equation.
[c] Maximal profit that can be obtained.

5.8.5 Model limitation

The inequalities in Constraints (5.6) to (5.9) imply that the optimal result does have some waste in terms of transportation capacity. For instance, m_1 which is capable to carried 60 t/d of WLM from i_3 to j_{12}, is used to deliver 10 t/d of sugarcane bagasse. A total 80 % of capacity is wasted for this particular case. In order to address this issue, joint transportation should be implemented. Figure 5.20 shows an example for the joint-transport design. From the figure, 2 t/d of product *p* is produced from each of the hubs (j_{16} and j_{17}). When no joint-transport is applied, two m_1 are used to deliver the product from each processing hub to the port (one m_1 for each processing hub). However, when joint-transport is applied, one m_1 is sufficient to carry all the products to the port. Table 5.17 summarises the performance of the joint transportation for this example. It shows a promising result for the joint transportation.

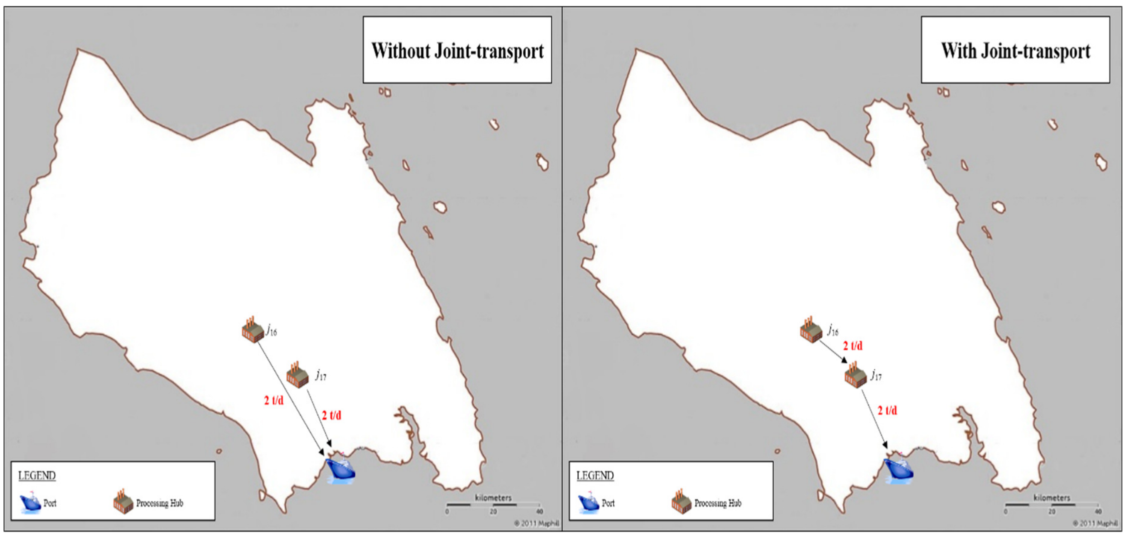

Figure 5.20: Joint-transport problem.

Table 5.17: Transportation cost and total carbon emission under different operation mode.

Parameter	Without joint-transport	With joint-transport
Number of vehicles	2 x m_1	1 x m_1
Carbon emission [tCO_2/y]	0.061	0.040
C^{Tr} [RM/y]	119,194	77,844

After applying joint transportation, the CO_2 emission is decreased by 34.2 % while the total transportation cost is reduced by 34.7 %. However, the proposed model is unable to provide a solution with joint-transportation. The current model has to be revised (Equations (5.6) to (5.9)) in order to allow multi-stop delivery between processing hubs. Therefore, a comprehensive framework or algorithm (e.g., nearest neighbour algorithm which is widely used to solve travelling salesman problem (Flood, 1956)) has to be developed in the future in order to optimise this joint-transportation problem.

5.8.6 Sensitivity analysis

5.8.6.1 Terrain profile

The urban and inter-city road in Johor is considered well developed. Table 5.18 shows the sensitivity study of terrain profile to the optimal results. The results show that obtained results is not sensitive to the terrain profile as it only affects the total transportation cost with no major change in transportation design.

Table 5.18: Variation of vehicle used under different terrain profile (Case 2).

Terrain	Number of vehicle					Optimal no. of hub	C^{Tr} [RM/y]
	m_1	m_2	m_3	m_4	m_5		
Severe downslope	17	3	2	96	3	3	26,136,902
Mild downslope	17	3	2	96	3	3	27,336,695
Flat	17	3	2	96	3	3	31,366,320
Mild upslope	17	3	2	96	3	3	36,594,250
Severe upslope	17	3	2	96	3	3	56,536,690

5.8.6.2 Weather change and traffic congestion

Both weather and traffic condition play the important role in driving speed. Therefore, sensitivity analysis for these two factors are carried out by assuming different average driving speed. The results given in Table 5.19 show that the average driving speed will not affect the selection of vehicle and the optimal number of processing hubs. However, the total number of vehicle required is higher when the vehicle is operated under lower average speed. Nevertheless, this effect can be minimised by having a proper route planning and scheduling (e.g., avoid delivery via jammed zone or during the peak period).

Table 5.19: Variation of vehicle used under different driving speed (Case 2).

Sp_m^{Mean} [km/h]	Number of vehicle					Optimal no. of hub	C^{Tr} [RM/y]
	m_1	m_2	m_3	m_4	m_5		
30	17	3	4	147	3	3	38,044,431
40	16	3	3	120	3	3	34,668,241
50	16	3	3	108	3	3	32,755,028
60	17	3	2	96	3	3	31,366,320

5.8.6.3 Fuel price fluctuation

The price of fuel continuously fluctuates and is incredibly difficult to forecast. The recent data (see Figure 5.8) shows the fuel pricing fluctuates between +30 % to -30 % of the current fuel price. Table 5.20 shows the sensitivity study of fuel price to the optimal result. Similar results are obtained for fuel price fluctuation between -30 % to +30 %. Therefore, it can be concluded that the result obtained from the proposed model is not sensitive to the fuel price fluctuation.

Table 5.20: Variation of vehicle used under different fuel price (Case 2).

C^{Fuel} [RM/L]	Number of vehicle					Optimal no. of hub	C^{Tr} [RM/y]
	m_1	m_2	m_3	m_4	m_5		
1.30	17	3	2	96	3	3	28,894,210
1.50	17	3	2	96	3	3	29,718,247
1.70	17	3	2	96	3	3	30,542,283
1.90	17	3	2	96	3	3	31,366,320
2.10	17	3	2	96	3	3	32,190,356
2.30	17	3	2	96	3	3	32,602,374
2.50	17	3	2	96	3	3	33,838,429

5.8.6.4 Individual environmental preference

Decision-makers can set different rate for carbon pricing based on their environmental preference. Table 5.21 shows the sensitivity check of carbon pricing to the obtained results. The carbon pricing used in this case study is about 0.20 [RM/kg CO_2] (value determined using method proposed by Zhou et al. (2015)). Same result is obtained after raising the carbon emission penalty to 1.00 [RM/ kg CO_2] (i.e., about 5 times of current carbon penalty. Hence, the obtained result is not sensitive to the value of the carbon pricing. This is not surprising because both transportation cost (without carbon penalty) and CO_2 emission are calculated based on two same factors, i.e., distant travel and daily delivered amount (see Equations (5.22) to (5.28), (5.30)).

Table 5.21: Variation of vehicle used under different carbon pricing (Case 2).

CO_2 penalty [RM/kg CO_2]	Number of vehicle					Optimal no. of hub	C^{Tr} [RM/y]
	m_1	m_2	m_3	m_4	m_5		
0	17	3	2	96	3	3	29,214,260
0.10	17	3	2	96	3	3	30,290,290
0.20	17	3	2	96	3	3	31,366,320
0.40	17	3	2	96	3	3	33,518,379
0.60	17	3	2	96	3	3	35,670,438
0.80	17	3	2	96	3	3	37,822,498
1.00	17	3	2	96	3	3	39,974,557

In short, due to the insignificant impact of the realistic factors on the decision-making, the result obtained from this model (or SVS diagrams) is considered reliable. However, it is recommended to review the model (or SVS diagrams) once every five years in order to ensure all data used in the model is up-to-date and improve the accuracy of cost estimation.

5.9 Conclusion

This chapter has addressed the issue of physical limitation of vehicle for the transportation design in SCM. The main contributions of this paper are stated as follow:

I. An improved mathematical model is proposed to determine (i) optimal biomass allocation networks; and (ii) optimal transportation decisions with the consideration of vehicle capacity constraint and carbon emission penalty.

II. A comparative study between the previous work and the current work is conducted in order to show the importance of having a detailed calculation of transportation rather than using a correlation cost constant. Without consideration of vehicle capacity constraints, the calculated transportation cost is unreliable, thus leading undesirable loss of profit.

III. A novel graphical decision-making tool (SVS diagrams) is developed in order to help decision-makers select the best transportation mode directly without re-running mathematical model. User manual of the tool are given in this paper as well.

IV. Sensitivity studies on five parameters are conducted to analyse the impact of these parameters on the result obtained from the proposed model (or SVS diagrams). The results show that the proposed model (and SVS diagrams) robust (optimal result is insensitive to the five parameters). However, regular revision on the model (and SVS diagrams) is necessary in order to assure the reliability of the result.

This study can be extended by considering (i) different environmental indicators (in Chapter 5) and (ii) social dimension (in Chapter 6) of the supply chain activities. Besides, effort should be done to optimise the joint transportation suggested in this study.

Chapter 6:

Economic & Environmental Evaluation:

Weighted Sum Model

6.1 Introduction

SSCM problem is a multi-objective optimisation (MOO) problem since the objectives of each sustainability dimension and (or) the objectives of each components under a same sustainability dimension can be conflicting. It is rarely existing a single solution that simultaneously satisfied all objectives. Therefore, achieving optimum for one objective requires compromise of other objectives. For examples, profit can be contradicting to safety cost or environmental impacts; total CF can be inversely correlated to the total FEF (Čuček et al., 2012c). Several approaches have been developed to solve MOO problems. The simplest way reported from the academicians is to convert the MOO problem into single objective optimisation (SOO) problem (Rangaiah, 2009). For instance, Dantus and High (1999) proposes a weighting method, i.e., assigning a weightage or sequence priority to each objective in order to transform a MOO problem which aim to minimise the environmental impact and maximise the annual profit of a methyl chloride plant, into a SOO problem; Notably, in the recent publications, Mavrotas (2009) and Esmaili et al. (2011) suggest to use ε-constraint method over other weighting approach in solving MOO problems; Some researcher suggest to transform MOO into SOO by converting all other objectives into a similar form of objectives (EPA, 2003). However, converting CF into economic form (i.e., carbon penalty in Chapter 5) can produce sub-optimal solution. Since the penalty cost is relatively lesser compared to the annual profit, the model will tend to ignore the environmental concern, causing zero mitigation of environmental impacts.

This chapter presents a systematic approach that integrates both economic and environmental concern in the supply chain by using weighted sum approach. Instead of only focusing on CO_2, this chapter incorporate other environmental indicators as well, such as GWP, ODP, TTP, etc. In addition, this chapter proposes a graphical illustration method to present the sustainability performance of the results. Both economic sustainability and environmental sustainability are expressed as vector. The remainder of this chapter is organised into eight sections. The problem statement of this work is presented in Section 6.2 while the research methodology used for this work is described in section 6.3. In Section 6.4, the mathematical model presented in previous chapters is modified. The description of the graphical representation for the sustainability of SCM is provided in Section 6.5. Section 6.6 outlines the information of the demonstrated case study. It is followed by the result and discussion in Section 6.7. Last but not least, concluding remarks are given in Section 6.8.

6.2 Problem Statement

The same problem described in Chapter 5 (refer to Section 5.2) is modified to include different categories of environmental impacts into the model. It is formally stated as follows: given a set of biomass types r supplied from a set of source points i is planned to be delivered through a set of transportation modes m to a set of processing hubs j. Then, it is converted into a set of intermediates l and a set of products p via a set of technologies t and t'. Finally, they are delivered to a set of customers k through a set of transportation mode m'. Throughout the entire process, a set of pollutants a is released to the environment and will cause a set of environmental issues which belong to a set of impact categories q. The generic superstructure of the modified model is shown in Figure 6.1.

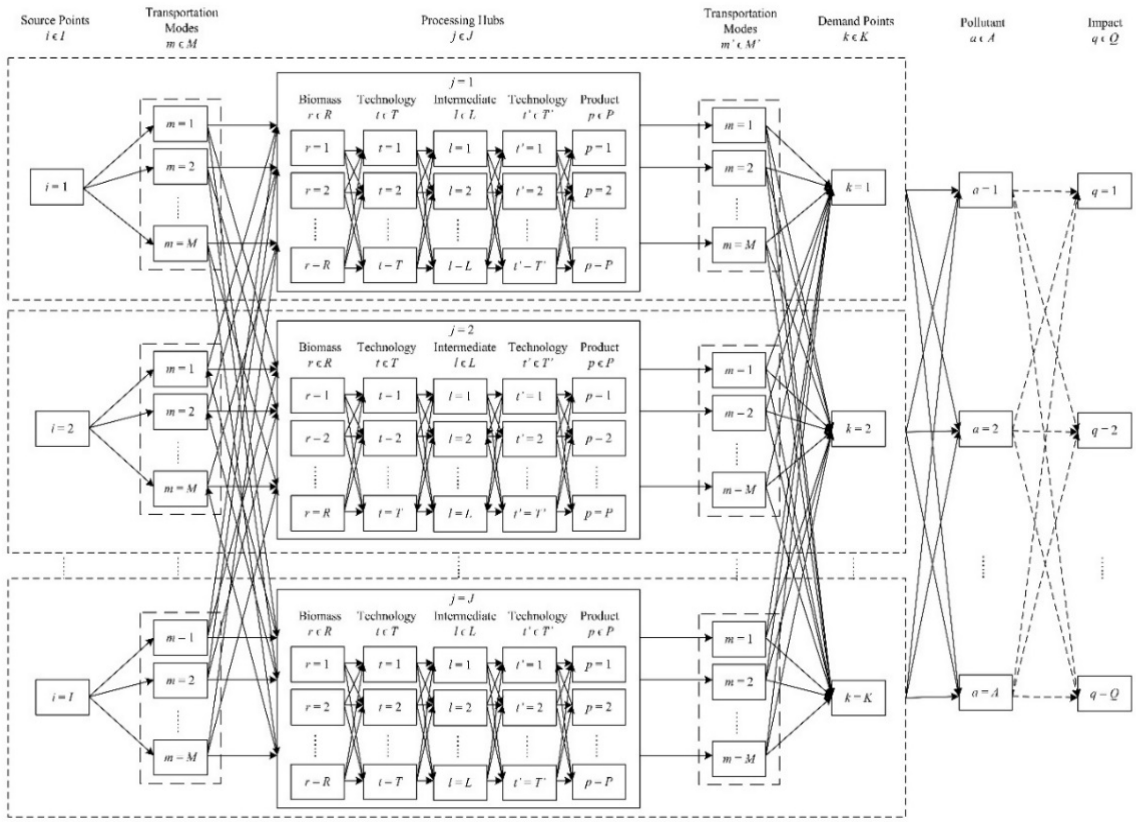

Figure 6.1: Generic superstructure of the proposed model (modified from Figure 5.1).

6.3 Methodology

The proposed model is re-formulated to consider different environmental impact simultaneously. The environmental impacts can be classified into several impact categories, i.e., global warming potential (GWP), ozone depletion potential (ODP), abiotic resource consumption (e.g., water, fossil fuel, etc.), eco-toxicity, etc. The detailed description of each indicator is given in Chapter 2 (see Section 2.4.3.1). In this chapter, weighted sum approach is used to model this multi-objective optimisation problem. Aside from this, different sets of priority scale are assigned to the objectives to investigate the effect of the priority scale on the optimal solutions. Figure 6.2 shows the overview of research method used in this chapter.

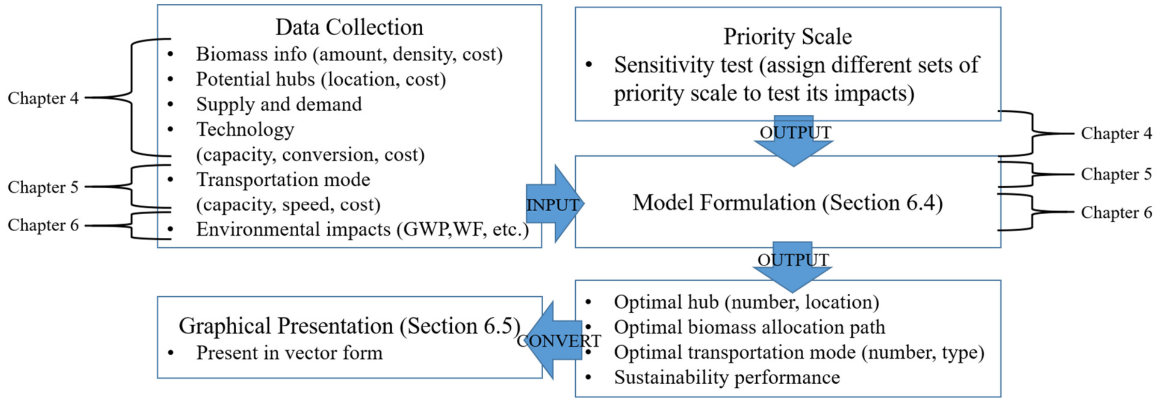

Figure 6.2: Overview of research method for Chapter 6.

6.4 Model Formulation

The model formulated in Chapter 4 and Chapter 5 is revised to integrate several potential environmental impacts (PEI) into the model. The problem is modelled through mixed integers linear programming (MILP) and is solved by using Lingo v14.0 (Lingo, 2015). It is formulated as:

6.4.1 Economic performance

The evaluation regarding to the economic performance will only consider 3 components, i.e., annual gross profit (C^{GP} [RM/y]), annualised hub investment cost, ($C^{\mathrm{Inv\_Hub}}$ [RM/y]) and annual transportation cost, (C^{Tr} [RM/y]). The environmental impact due to carbon emission will be evaluated separately in Section 6.4.2, thus the carbon emission penalty $C^{\mathrm{Penalty\_CO_2}}$ [RM/y] is removed from Equation (5.33). The economic performance of the synthesised supply chain is expressed as:

$$C^{\mathrm{NP}} = C^{\mathrm{GP}} - C^{\mathrm{Inv\_Hub}} - C^{\mathrm{Tr}} \tag{6.1}$$

The detailed calculation for each component is explained in the previous chapters (C^{GP} : Equation (4.12); $C^{\text{Inv\_Hub}}$: Equation (4.15); C^{Tr}: Equations (5.22) to (5.28)).

6.4.2 Environmental performance

The evaluation of environmental performance takes into account different categories of environmental impact *q*, which initially classified by Heijungs et al. (1992), i.e., global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), acidification potential (AP), eutrophication potential (so-called nutrification potential (NP)), abiotic depletion potential (ADP), aquatic toxicity potential (ATP) and terrestrial toxicity potential (TTP). However, this impact categories did not cover the environmental impact due to the water usage in the system, as well as the environmental impact due to the land usage for the construction of hub. Thus, water footprint (WF) and land footprint (LF) is evaluated in this model as well.

6.4.2.1 Environmental impact category

In general, the environmental impact from impact category *q*, EI_q [t-eq/y] of the entire supply chain consider 4 components, i.e., environmental impact due to the pollutant emitted from the conversion process, EI_q^{Process} [t-eq/y]; potential environmental impact due to manufactured product, EI_q^{Prod} [t-eq/y]; environmental impact due to the energy consumption in the hub, EI_q^{Elec}[t-eq/y]; and environmental impact due to the fuel consumption during transportation of biomass *r* and product *p*, EI_q^{Tr}. It is defined as follow:

$$EI_q = EI_q^{\text{Process}} + EI_q^{\text{Prod}} + EI_q^{\text{Elec}} + EI_q^{\text{Tr}} \qquad \forall q \in Q \qquad (6.2)$$

EI_q^{Process} can be determine by accounting the total potential environmental impacts of each pollutant *a* which are emitted from the conversion process in the processing hub *j*. It is expressed as:

$$EI_q^{\text{Process}} = \sum_a (F_a \times \Psi_{a,q}) \qquad \forall q \in Q \qquad (6.3)$$

$$F_a = \left\{\sum_{t'}\left(\sum_l \sum_j F_{l,t',j} \times \text{fac}_{a,t'}\right) + \sum_t\left(\sum_r \sum_j F_{r,t,j} \times \text{fac}_{a,t}\right)\right\} \times \text{OPD} \qquad \forall a \in A \qquad (6.4)$$

where F_a [t/y] refers to the total emission rate of the pollutants *a*, emitted to the aquatic, terrestrial and atmospheric environment during the conversion process in the processing hub *j*; $\Psi_{a,q}$ [t-eq/t] refers to the score of potential environmental impact of pollutant *a* at category *q*; while $\text{fac}_{a,t'}$ [t pollutant *a*/t intermediate *l*] and $\text{fac}_{a,t}$ [t pollutant *a*/t biomass *r*] refer to the emission factor of pollutant *a* through technology *t'* and *t*. Note that the degree of the impact is expressed as the equivalent amount of a reference component (e.g., GWP is expressed as unit mass of CO_2 equivalents; ODP is expressed as unit mass of CFC-11 equivalents; ADP is expressed as unit mass of Kr equivalents).

EI_q^{Prod} concerns the overall environmental impact caused by the product. It involves the direct effect (environmental-burdening) and indirect effect (environmental-unburdening) on the environment.

$$EI_q^{\text{Prod}} = EI_q^{\text{Prod\_Direct}} + EI_q^{\text{Prod\_Indirect}} \qquad \forall q \in Q \qquad (6.5)$$

where $EI_q^{\text{Prod\_Direct}}$[t-eq/y] refers to the direct environmental impact q caused by the product; while $EI_q^{\text{Prod\_Indirect}}$ [t-eq/y] refers to the indirect environmental impact q caused by the product.

$$EI_q^{\text{Prod\_Direct}} = \sum_p (\sum_j F_{p,j} \times \Psi_{p,q}) \times \text{OPD} \qquad \forall q \in Q \qquad (6.6)$$

$EI_q^{\text{Prod\_Direct}}$ is determined by multiplying the product flow in hub j to the score of potential environmental impact caused by the production, $\Psi_{p,q}$ [t-eq/t].

$$EI_q^{\text{Prod\_Indirect}} = -F^{\text{FossilFuel\_Sub}} \times \Psi_q^{\text{Fossil}} \qquad \forall q \in Q \qquad (6.7)$$

Indirect effect of a product refers to the unburdening related to the substitution of conventional non-renewable fossil energy. For example, the production of biofuels (e.g., bio-ethanol, py-oil, etc.) can cause a significant direct burden to the environment, but at the same time, the more harmful fossil-based energy is replaced by these biofuels and thus, unburden the environment indirectly (Čuček et al., 2012c). It is described in Equation (6.7), where $F^{\text{FossilFuel\_Sub}}$ [t/y] refers to the amount of fossil-based fuel being substituted by the biofuel generated; while Ψ_q^{Fossil} [t-eq/t] refers to the score of potential environmental impact caused by the utilisation of fossil-based energy. It is worth noting that the negative sign of $EI_q^{\text{Prod\_Indirect}}$ indicates that the substitution of fossil-based fuel is beneficial to the environment.

Electricity is imported from external power plant and (or) self-generated through power generation unit (steam turbine, etc.) in order to meet the electricity demand of the processing hub. Since coal power plant is one of the main energy source in Malaysia (Energy Commission, 2014), it is assumed as the electricity supplier in this work.

$$EI_q^{\text{Elec}} = (Elec^{\text{Imp}} - Elec^{\text{Gen}}) \times \Psi_q^{\text{Fossil}} \qquad \forall q \in Q \qquad (6.8)$$

EI_q^{Elec} considers the environmental impact which attributed by imported energy, $Elec^{\text{Imp}}$ [MJ/y] and the environmental unburdening effect of the self-generated bio-electricity, $Elec^{\text{Gen}}$ [MJ/y].

$$Elec^{\text{Exp}} = Elec^{\text{Imp}} + Elec^{\text{Gen}} - Elec^{\text{Req}} \qquad (6.9)$$

Equation (6.9) shows the generic energy balance in the processing hub, where $Elec^{\text{Req}}$ [MJ/y] refers to the total electricity required in the processing hub; while $Elec^{\text{Exp}}$ [MJ/y] refers to the total excess energy that can be sold.

$$Elec^{\text{Req}} = \left\{\sum_{t'}(\sum_l \sum_j F_{l,t',j} \times \text{Y}_{t'}^{\text{Elec}}) + \sum_t(\sum_r \sum_j F_{r,t,j} \times \text{Y}_t^{\text{Elec}})\right\} \times \text{OPD} \qquad (6.10)$$

The total energy required is calculated by using Equation (6.10), where $\text{Y}_{t'}^{\text{Elec}}$ [MJ/t] and Y_t^{Elec} [MJ/t] refer to the electricity requirement for technology *t'* and technology *t*.

$$Elec^{\text{Gen}} = \left\{\sum_{t'}(\sum_l \sum_j F_{l,t',j} \times \text{X}_{l,t'}^{\text{Elec}}) + \sum_t(\sum_r \sum_j F_{r,t,j} \times \text{X}_{r,t}^{\text{Elec}})\right\} \times \text{OPD} \qquad (6.11)$$

The total generated energy is determined by using Equation (6.11), where $\text{X}_{l,t'}^{\text{Elec}}$ [MJ/t] and $\text{X}_{r,t}^{\text{Elec}}$ [MJ/t] refer to the energy conversion factor of intermediate *l* and biomass *r* in technology *t'* and *t* respectively.

Transporting biomass *r* and product *p* from source *i* to processing hub *j*, and from processing hub *j* to customer *k* required to consume a significant amount of fossil-based fuel. EI_q^{Tr} considers the environmental impact caused by the usage of petrol fuel:

$$EI_q^{\mathrm{Tr}} = F^{\mathrm{Fuel}} \times \Psi_q^{\mathrm{Fossil}} \qquad \forall q \in Q \tag{6.12}$$

$$F^{\mathrm{Fuel}} = 2 \times \mathrm{OPD} \times \Big\{\sum_i \sum_m \sum_j (\mathrm{d}_{i,j} \times num_{i,m,j}^{\mathrm{Trip}} \times \mathrm{rate}_m^{\mathrm{Fuel}}) + \sum_j \sum_{m'} \sum_k (\mathrm{d}_{j,k} \times num_{j,m',k}^{\mathrm{Trip}} \times \mathrm{rate}_{m'}^{\mathrm{Fuel}})\Big\} \tag{6.13}$$

where F^{Fuel} [L/y] refers to the total annual fuel consumed for the transportation. The score of each material's potential environmental impact at category *q*, including $\Psi_{a,q}$, $\Psi_{p,q}$, and $\Psi_q^{\mathrm{Fossil}}$are obtained from the WAR algorithm software (WAR GUI, 2011) developed by the U.S. Environmental Protection Agency.

6.4.2.2 Environmental footprints

This work also concerns on the total water consumption required in each technology in the processing hub. It can be expressed in terms of total water footprint of the supply chain, WF^{Total} [m^3/y] which normally used to measure the total water volume consumed per unit of time of the system (Galli et al., 2012). It is defined as:

$$WF^{\mathrm{Total}} = \Big\{\sum_{t'} (\sum_l \sum_j F_{l,t',j} \times \mathrm{Y}_{t'}^{\mathrm{Water}}) + \sum_t (\sum_r \sum_j F_{r,t,j} \times \mathrm{Y}_t^{\mathrm{Water}})\Big\} \times OPD \tag{6.14}$$

where $\mathrm{Y}_{t'}^{\mathrm{Water}}$ [m^3/t] refers to the water requirement for technology *t'*; while $\mathrm{Y}_t^{\mathrm{Water}}$ [m^3/t] refers to the water requirement for technology *t*.

The environmental impact caused by the settlement of the processing hub should be considered as this might affect the optimal number of processing hub in the proposed case study. Hence, the total land footprint of the supply chain, LF^{Total} [m^2] which measure the total land area that covered by the infrastructure of the processing hub are used as an indicator to represent the environmental impact of land use. Note that the estimated land area required for setting up a single processing hub, $\mathrm{Area}^{\mathrm{Hub}}$ [m^2/hub] is assumed to be 20,000 m^2/hub in this case study.

$$LF^{\mathrm{Total}} = \sum_j B_j \times \mathrm{Area}^{\mathrm{Hub}} \tag{6.15}$$

6.4.3 Multi-objective approach

The objective function of this work is the overall degree of satisfaction based on the sustainability performance of the biomass supply chain, λ^{SCM}. It is described as:

$$max\ \lambda^{\mathrm{SCM}} = \mathrm{w}^{\mathrm{Ec}} \times \lambda^{\mathrm{Ec}} + \mathrm{w}^{\mathrm{En}} \times \lambda^{\mathrm{En}} \tag{6.16}$$

$$w^{\mathrm{Ec}} + w^{\mathrm{En}} = 1 \tag{6.17}$$

where λ^{Ec} and λ^{En} refer to the degree of satisfaction of the biomass supply chain based on economic performance and environmental performance respectively; while w^{Ec} and w^{En} refer to the relative priority assigned to both objectives.

$$\lambda^{\mathrm{Ec}} = \frac{C^{\mathrm{NP}} - \mathrm{C}^{\mathrm{NP(L)}}}{\mathrm{C}^{\mathrm{NP(U)}} - \mathrm{C}^{\mathrm{NP(L)}}} \tag{6.18}$$

λ^{Ec} concerns the net profit gained from the supply chain, C^{NP} [RM/y]. It is described in Equation (6.18), where $\mathrm{C}^{\mathrm{NP(U)}}$ [RM/y] and $\mathrm{C}^{\mathrm{NP(L)}}$ [RM/y] refer to the maximal and minimal net profit that can be gained from the synthesised supply chain respectively. These values are obtained by maximising and minimising C^{NP} through the mathematical model (i.e., Equation (6.1)). It is worth to note that Equation (6.18) is a maximisation case of objective, it can be visualised as Figure 6.3 (L).

$$\lambda^{\mathrm{En}} = \sum_q \left(\frac{\mathrm{EI}_q^{(\mathrm{U})} - EI_q}{\mathrm{EI}_q^{(\mathrm{U})} - \mathrm{EI}_q^{(\mathrm{L})}} \times \mathrm{w}_q\right) \tag{6.19}$$

λ^{En} indicates the degree of satisfaction of the biomass supply chain based on environmental perforamnce, where $\mathrm{EI}_q^{(\mathrm{U})}$ [t-eq/y] and $\mathrm{EI}_q^{(\mathrm{L})}$ [t-eq/y] refer to the upper limit and the lower limit of the environmental impact at category q caused by the entire supply chain respectively (obtained by maximising and minimising EI_q through the Equation (6.2)), while w_q refers to the relative importance of each environmental impact. Note that Equation (6.19) is the minimisation case of objective, it can be visualized as Figure 6.3 (R).

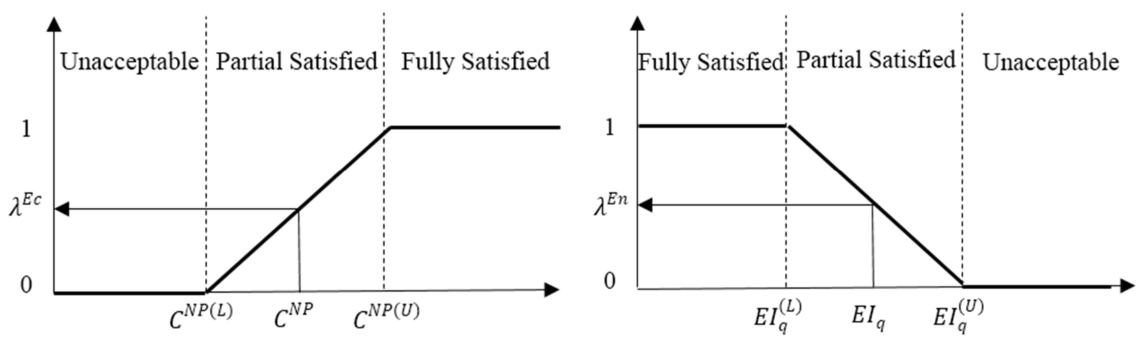

Figure 6.3: Degree of satisfaction for (L) maximisation case; (R) minimisation case.

6.5 Graphical Representation: Sustainability Vector (*s*-vector)

In this work, the result (sustainability performance) is expressed as a vector form. The conceptual idea is described in the sub-sections below:

6.5.1 Concept of s-vector

To-date, several methods are used to present the sustainability of the system. For instance, De Benedetto and Klemeš (2015) introduce the Environmental Performance Strategy Map (ESPM) which present the ecological footprints on a specific spider web; Chardine-Baumann and Botta-Genoulaz (2014) express the economic-environmental-social performance of the process as a triad; Tjan et al. (2010) present carbon footprint composite curve with economic value on the horizontal axis and CO_2 emission on the vertical axis. These works are decent, but the current approaches did not show a clear view regarding to the tendency of the system or process toward each of the sustainability dimension. Therefore, this work suggests to present the results in a vector form which consist of magnitude and direction. It can be expressed in cartesian form Vector(Obj^{Ec}, Obj^{En}) or in polar form as Vector(Mag, θ). Note that Obj^{Ec} and Obj^{En} refer to the overall performance in economic-objective and environmental-objective respectively. They are defined as:

$$Obj^{\mathrm{Ec}} = \frac{\lambda^{\mathrm{Ec}} - \lambda^{\mathrm{Ec(Ref)}}}{1 - \lambda^{\mathrm{Ec(Ref)}}} \tag{6.20}$$

$$Obj^{\mathrm{En}} = \frac{\lambda^{\mathrm{En}} - \lambda^{\mathrm{En(Ref)}}}{1 - \lambda^{\mathrm{En(Ref)}}} \tag{6.21}$$

where value “1” in the dominator represent the maximum value of the degree of satisfaction; while $\lambda^{\mathrm{Ec(Ref)}}$ and $\lambda^{\mathrm{En(Ref)}}$ represent the degree of satisfaction when zero effort is committed (i.e., processing plant is not set-up, biomass is not collected and processed, etc.). Therefore, any positive attributes (e.g., profit gained, negative carbon footprint) will lead to positive value in the vector; contrarily, any negative attributes (e.g., profit loss, carbon emission) will lead to negative value in the vector.

θ is the angle that reveals the tendency of the system toward economic or environmental dimension; while Mag refer to the magnitude of the sustainable vector (s-vector). They can be determined by using Equations (6.22) and (6.23). Figure 6.4 represents an s-vector of a process which contain 0.8 and 0.5 for the degree of satisfaction based on economic and environmental dimensions respectively (assume $\lambda^{\mathrm{Ec(Ref)}}$ and $\lambda^{\mathrm{En(Ref)}}$ are both equal to 0).

$$\theta = tan^{-1}(\frac{Obj^{\mathrm{En}}}{Obj^{\mathrm{Ec}}}) \tag{6.22}$$

$$Mag = \sqrt{Obj^{\mathrm{Ec}^2} + Obj^{\mathrm{En}^2}} \tag{6.23}$$

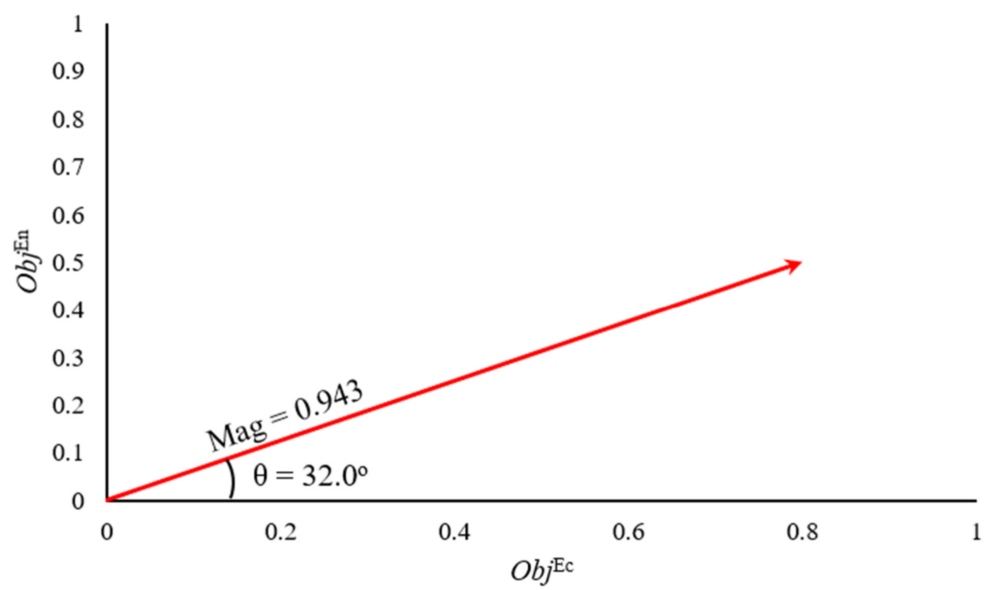

Figure 6.4: Sustainability vector.

6.5.2 Quadrant diagram for s-vector

After converting the results into vector form, the newly formed vectors can be plotted in a quadrant diagram. Decision-makers can now classify the activities based on this graphical representation tool. Figure 6.5 demonstrates the quadrant diagram which representing the vector for each activity.

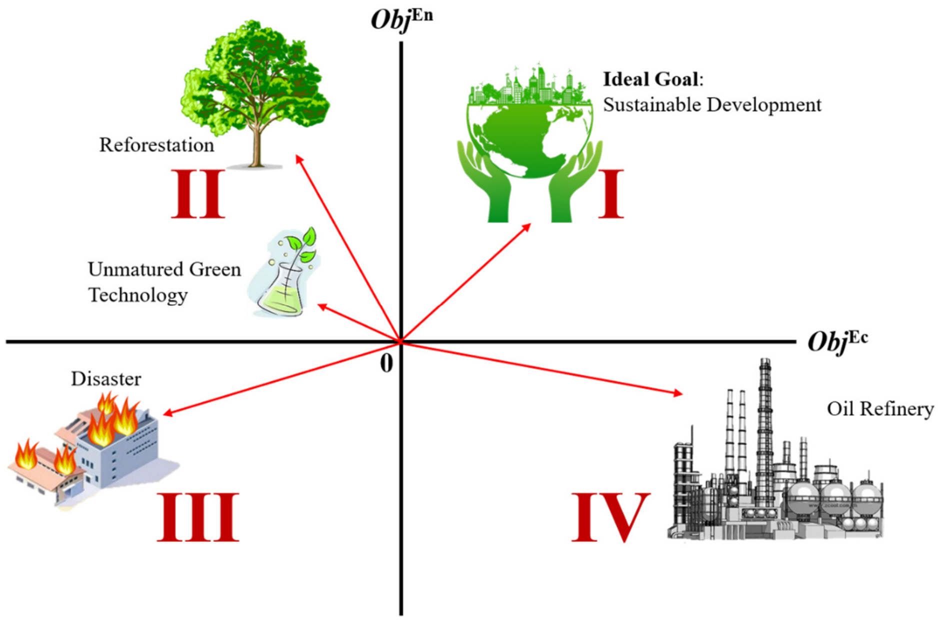

Figure 6.5: Quadrant diagram for *s*-vector.

To illustrate, the conventional practices that often relied on fossil-based energy are normally plotted on the forth quadrant (positive attribute on economic but negative attribute to environment). On the other hand, the activities that fall on second quadrant are related to some of the non-economically profitable "green policies" (e.g., reforestation) that araised by the environmentalists. In addition, the unmatured green technologies which are yet to be economic-feasible and other treatment facilities (e.g., wastewater treatment) also fall on this quadrant. The activities that falls on the third quadrant should be avoided since these activities will lead to negative impact on both economic and environmental objectives. Disasters, such as plant fire and explosion will fall on this quadrant as well. Last but not least, the ideal goal is to emerge the green technologies into the first quadrant (provide positive attribute to both objectives), in order to enhance the sustainable development.

6.5.3 Process evaluation using s-vector

s-vector can be used to evaluate the sustainability performance of each process. In the first quadrant, the process with a smaller θ, indicate that this process has a higher tendency toward economic sustainability. Therefore, decision-makers can select the process path which meet their personal preference in each sustainability dimension based on this θ value. For processes with same or near-range of θ (+-5^{o}), Mag is used as selection reference as the process with larger Mag indicates that the degree of satisfaction on both economic and environmental dimensions of this process is relatively higher.

Figure 6.6 presents the s-vector of three possible process pathways (i.e., process 1, process 2 and process 3) for Material A. The s-vector for process 1, process 2 and process 3 are Vector(0.943, 32.0^{o}), Vector(1.005, 5.7^{o}) and Vector(0.500, 36.9^{o}) respectively. From these values, it is obviously shown that process 2 has the smallest θ. In other words, this process might attribute to high profit but also caused severe environmental issues. Although the θ value for Process 1 and Process 3 are similar, Process 1 is more favourable than Process 3 due to its higher magnitude compared to Process 3.

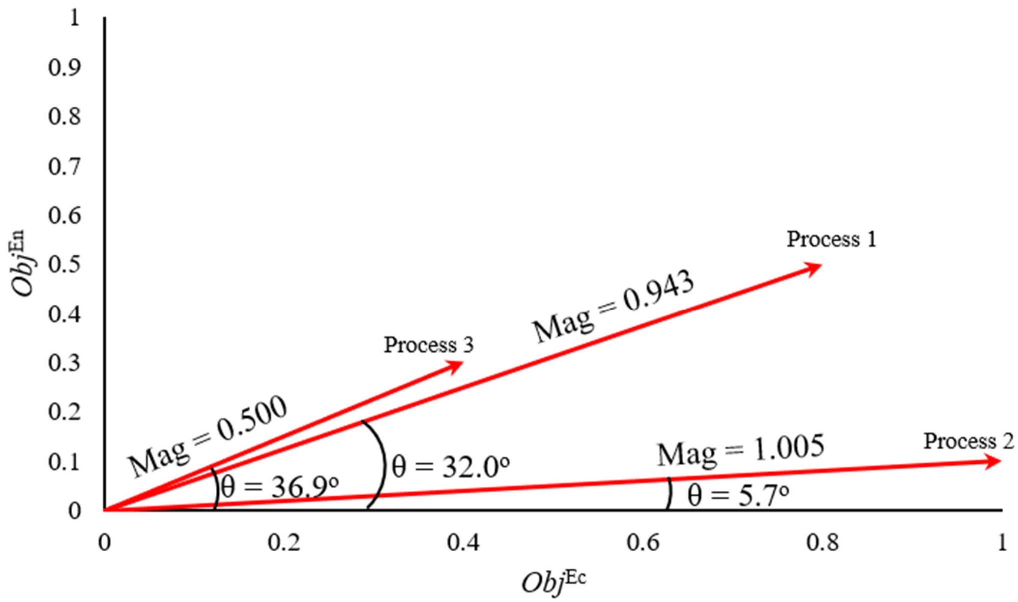

Figure 6.6: Comparison of *s*-vector.

Note that for second quadrant (90°< θ <180°), smaller θ indicates better performance in environmental sustainability (but with negative economic sustainability); for forth quadrant (270°<θ<360°), larger θ indicates better performance in economic sustainability (but with negative environmental sustainability); while for third quadrant (180°< θ <270°), smaller θ indicate that this process has a higher tendency toward environmental sustainability.

6.5.4 Sustainabiloty targeting for integrated process

In some cases where process integration is taking part, the sustainability performance of this integrated process can be determined easily through *s*-vector. By taking the example shown in Figure 6.6, assume 60 % of material A are sent to process 1, whereas the remaining are sent to process 2. The sustainability performance of this integrated process can be targeted merely by adding 60 % of Vector(0.943, 32.0°) and 40 % of Vector(1.005, 5.7°) together (as illustrated in Figure 6.7).

It can also be defined mathematically, where n denote the process alternatives; frac_n refers to the weight fraction of the material which sent to process n; Mag_n and θ_n are the magnitude and angle of the *s*-vector for process n; while Mag^{New} and θ^{New} are the magnitude and angle of the *s*-vector for the integrated process:

$$\theta^{New} = tan^{-1}\left(\frac{\sum_n \mathrm{frac}_n \, Mag_n \, Cos \, \theta_n}{\sum_n \mathrm{frac}_n \, Mag_n \, Sin \, \theta_n}\right) \quad (6.24)$$

$$Mag^{New} = \sqrt{(\sum_n \mathrm{frac}_n \, Mag_n \, Cos \, \theta_n)^2 + \sum_n \mathrm{frac}_n \, Mag_n \, Sin \, \theta_n{}^2} \quad (6.25)$$

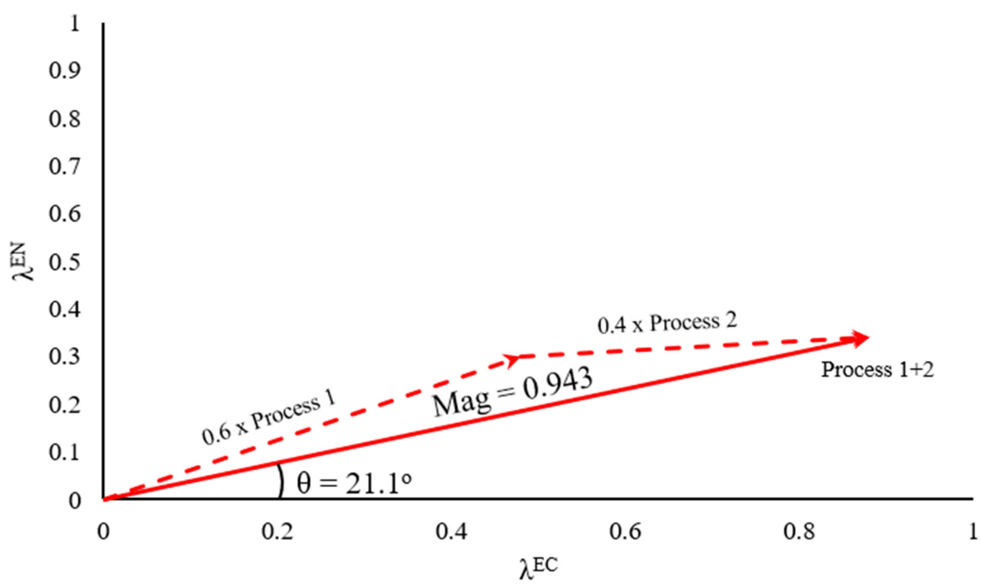

Figure 6.7: s-vector for integrated processes.

6.6 Case Study Description

The same case study in Johor state is extended to study the potential environmental impacts caused by the activities in the supply chain. The sources of each environmental impact (i.e., GWP, ODP, POCP, AP, NP, ADP, ATP, TTP, WF and LF) are discussed in this subsection:

6.6.1 Global warming potential (GWP)

The effects of the greenhouse gases (GHG) that trap heat in the atmosphere (e.g., CO_2 and CH_4) are normalised and reported in terms of GWP. In SCM, GHG is mainly emitted from the burning of fossil-based fuel, such as the utilisation of petrol in vehicles during transportation of materials; and the utilisation of electricity generated from the coal power plant. Besides, GHG is emitted during the conversion processes, e.g., pyrolysis, fermentation, combustion, etc. (see Table 6.1).

6.6.2 Ozone depletion potential (ODP)

Refrigerant such as chlorofluorocarbon (CFCs) and hydrofluorocarbon (HFCs) are the main contributors which caused the ozone depletion. However, the needs of using these environmental-harmful refrigerants is evitable due to the hot weather in Malaysia (about 35 ^{o}C). To-date, there are several types of refrigerants available in the market. In early-20th century, R-12 is often used as the refrigerants in the automotive air-conditioning system. However, due to its high ozone depletion rate, it is now replaced by R134A which contain zero ODP and lower GWP (i.e., 8 times lesser than R-12) (World Bank Group, 1998). By using this relatively "cleaner" refrigerant, ODP of the SCM is negligible. Table 6.2 shows the comparison of the refrigerants based on their ODP and GWP.

Table 6.1: GHG emissions.

SCM Activities	GHG Emission [g/kg biomass]					Reference
	CO_2	CH_4	CO	N_2O	R134A	
DLF/Energy Pack Production[a]	0.00	0.00	0.00	0.00	0.00	-
Gasification[a]	588.6	0.0054	0.0803	0.00	0.00	(NCPC, 2014)
Fast Pyrolysis[a]	463	0.0030	0.0580	0.00	0.00	(Steele et al., 2012)
Slow Pyrolysis[a]	404	0.0037	0.0549	0.00	0.00	(NCPC, 2014)
Bio-ethanol Production (Fermentation)[a]	1,126[c]	1.124[c]	0.305[c]	0.00	0.00	(Kadam, 2000) (Wang et al., 2013)
	1,205[d]	1.132[d]	0.316[d]	0.00	0.00	
	1,154[e]	0.121[e]	0.324[e]	0.00	0.00	
	865.6[f]	1.100[f]	0.218[f]	0.00	0.00	
Citric Acid Production	300	0.030	0.081	0.00	0.00	(Prado et al., 2005)
Biogas-to-energy[a,b,i]	970 [g]	23[g]	0.471	0.003	0.00	(EPA, 1998)
Transportation [g/L fuel]	2,600	0.56	276.8	0.028	88[h]	(Canada, 2013)
Importing energy [g/kWh]	967	0.01	0.12	0.014 5	0.00	(Qin et al., 2006)
Combustion[i]	1,585	5.82	102	0.00	0.00	(Akagi et al., 2011)
GWP [CO_2-eq]	1	25	2	296	1,320	(Azapagic et al., 2005)

[a] Value did not account the GHG contributed from the energy required.
[b] Assume biogas consist of 70 vol% CH_4 and 30 vol% CO_2 (De Mes et al., 2003).
[c] Undergo dilute acid pre-treatment. [d] Undergo dilute alkaline pre-treatment.
[e] Undergo hot water pre-treatment. [f] Undergo steam explosion pre-treatment.
[g] 90% of CH_4 will be converted into energy and CO_2.
[h] Overall estimated emission rate of the refrigerant [g/vehicle.y] (Schwarz, 2001).
[i] Carbon emission is assumed as 0 as the biogenic-methane will not contribute to the net release of Carbon in the Carbon Cycle (Zaimes & Khanna, 2015).

Table 6.2: Refrigerants available in market (Daikin Group, 2013).

Refrigerant	GWP [CO_2-eq]	ODP [CFC-11-eq]	Flammable
R12	10,900	1	No
R22	1,810	0.055	No
R410A	2,090	0	No
R134A	1,320	0	No
R290	3.3	0	Yes

6.6.3 Photochemical ozone creation potential (POCP)

The increase concentration of volatile organic compounds (VOCs) and nitrogen oxides (NO_x) in atmosphere might cause the formation of ground-level ozone. Although there is study shows that the concentration of ground-level ozone is still below the permissible values, but it is still recommended to have a regular monitoring of the gas emission (Awang et al., 2015). The VOCs (e.g., CO and CH_4) and NO_x emissions in the supply chain are summarised in Table 6.3.

6.6.4 Acidification potential (AP)

In Malaysia, acid rain is mostly caused by the combustion of fossil fuel which will generate vast amount of acidic gases (e.g., NO_x, SO_x, etc.). Malaysia Natural Resources and Environmental Minister, Datuk Wan Junaidi claimed that Malaysia is currently not at risk of having acid rain as the air pollution index for Malaysia is still within the acceptable range (Newsunited, 2015). However, it is still essential to monitor and control the acidic gases emission throughout the SCM activities. Table 6.4 shows the AP of the waste gas emitted.

Table 6.3: VOCs and NO_x emissions.

SCM Activities	Emission [g/kg biomass]					Reference
	NO_x	CH_4	CO	SO_2	HCs[a]	
DLF/Energy Pack production	0.00	0.00	0.00	0.00	0.00	-
Gasification	0.0803	0.0054	0.0803	0.0054	0.0054	(NCPC, 2014)
Fast pyrolysis	0.0553	0.0030	0.058	0.0030	0.0030	(Steele et al., 2012)
Slow pyrolysis	0.0549	0.0037	0.0549	0.0037	0.0037	(NCPC, 2014)
Bio-ethanol Production (Fermentation)	0.305[b]	1.124[b]	0.305[b]	0.775[b]	0.00	(Kadam, 2000) (Wang et al., 2013)
	0.312[c]	1.132[c]	0.316[c]	0.675[c]	0.00	
	0.324[d]	0.121[d]	0.324[d]	0.513[d]	0.00	
	0.218[e]	1.100[e]	0.218[e]	0.796[e]	0.00	
Citric Acid Production	0.080	0.030	0.081	0.121	0.00	(Prado et al., 2005)
Biogas-energy generation[f]	0.561	0.023	0.00	0.003	0.4709	(EPA, 1998)
Transportation [g/L fuel]	4.408	0.56	276.8	0.017	6.851	(EPA, 2008)
Importing energy [g/kWh]	4.38	0.01	0.12	7.95	0.213[g]	(Qin et al., 2006)
Combustion	3.11	5.82	102	0.00	25.406	(Akagi et al., 2011)
POCP [ethene-eq]	0.028	0.006	0.030	0.048	0.416	(Azapagic et al., 2005)

[a] Hydrocarbons exclude CH_4.
[b] Undergo dilute acid pre-treatment.
[c] Undergo dilute alkaline pre-treatment.
[d] Undergo hot water pre-treatment.
[e] Undergo steam explosion pre-treatment.
[f] Assume biogas consist of 70 vol% CH_4 and 30 vol% CO_2 (De Mes et al., 2003).
[g] Data obtained from Spath et al. (1999).

Table 6.4: Acidification potential (AP) of the waste gas.

Waste gas	AP [SO_2-eq]	Reference
NO_x	1.10	(WAR GUI, 2011)
SO_2	1.00	
Hydrocarbon	0.018	(NCPC, 2014)

6.6.1 Neutification Potential (NP)

The over-fertilisation of water and soil is often due to the increase concentration of chemicals, including phosphates, nitrates, NO_x and chemical oxygen demand (COD). The emission rate of these "nutritious" substances are tabulated in Table 6.5.

6.6.2 Aquatic toxicity potential (ATP) and terrestrial toxicity potential (TTP)

ATP and TTP are used to measure the impacts of eco-toxicity in different medium. As suggested by Young and Cabezas (1999), ATP was estimated by using the toxicological data for a fish species, named as *Pinephales promelas*. The data is described as the form of LC_{50} [mg/L], i.e., the lethal concentration which caused 50 % death of this fish specimens. Similarly, TTP is estimated by using the LD_{50} [mg/kg], i.e., the lethal dose that caused 50 % death of rat specimens by oral ingestion. The ATP and TTP scores for each material summarised in Table 6.6. They are defined as:

$$\Psi_{a,q=ATP} = \frac{1}{\mathrm{LC}_{50\,a}} \tag{6.26}$$

$$\Psi_{a,q=TTP} = \frac{1}{\mathrm{LD}_{50\,a}} \tag{6.27}$$

where $\Psi_{a,q=ATP}$ [L/mg] refers to the ATP score of pollutant a; while $\Psi_{a,q=TTP}$ [kg/mg] refers to the TTP score of pollutant a.

Table 6.5: Emission of the eutrophicating substances.

SCM Activities	Emission [g/kg biomass]		Reference
	NO_x	COD	
DLF/Energy Pack Prod.	0.00	60	(Turunen & van der Wert, 2006)
Gasification	0.083	60	(NCPC, 2014)
Fast pyrolysis	0.0553	60	(Steele et al., 2012)
Slow pyrolysis	0.0549	60	(NCPC, 2014)
Bio-ethanol Production (Fermentation)	0.305[a]	252.6[a,e]	(Wang et al., 2013)
	0.312[b]	255.8[b,e]	
	0.324[c]	255.3[c,e]	
	0.218[d]	230.2[d,e]	
Citric Acid Production	0.080	263	(Prado et al., 2005)
Biogas-energy generation[f]	0.561	-2.522[f]	(EPA, 1998)
Transportation [g/L fuel]	4.408	0.00	(EPA, 2008)
Importing energy [g/kWh]	4.38	0.0018	(Spath et al., 1999)
Combustion	3.11	0.02	(Akagi et al., 2011)
NP [PO_4^{3-}-eq]	0.13	0.022	(Azapagic et al., 2005)

[a] Undergo dilute acid pre-treatment. [b] Undergo dilute alkaline pre-treatment.
[c] Undergo hot water pre-treatment. [d] Undergo steam explosion pre-treatment.
[e] 10L of stillage is produced for every L of ethanol (Tomczak-Wandzel et al., 2015).
[f] Biogas conversion: 228 g biogas/kg COD (Wang et al., 2013).

Table 6.6: Toxicity potential of the substances.

Substances	ATP [L/mg] [a]	TTP [kg/mg] [a]
DLF	0.00	0.00
Energy Pack	0.00	0.00
Py-oil	0.1639[b]	2.0408[b]
Bio-char	0.9523 E-03[c]	1.2903E-04[c]
Syngas	0.00	0.00
Bio-ethanol	7.2254 E-05	1.1185 E-04
Citric acid	3.6101 E-03	1.4859 E-04
Sulphuric acid[d]	0.04	4.6729 E-04
R134A	2.0534 E-03	0.00

[a] All scores are obtained from WAR GUI, build 1.0.17 (WAR GUI, 2011).
[b] Scores of naphthalene which is the key component of py-oil are used.
[c] Assume 1 kg bio-char contain 20g of potassium (Chan & Xu, 2009).
[d] Emitted from bio-ethanol production, the emission rate [g/kg biomass] is 0.1503[a]; 0.032[b]; 0.0993[c]; 0.1540[d].

6.6.3 Abiotic depletion potential (ADP)

Abiotic resource depletion encompasses both the utilisation of non-renewable and renewable abiotic resources, but for this work, we will only focus on the utilisation of fossil energy only. Guinée et al. (2002) suggest to use baseline characterisation method to measure the ADP of the materials. In this method, the extraction of the fossil fuels is defined as a relative measure with the depletion of antimony (Kr) as a reference (Pikoń, 2012). The ADP score for the use fossil energy is reported as 0.0134 kg Kr-eq/ kg coal and 0.021 kg Kr-eq/ kg fuel (van Oers et al., 2002).

6.6.4 Water use

Due to the large and growing population in Asia countries, the fresh water demand is increasing significantly from time to time. However, the annual availability of fresh water is limited. Therefore, it is necessary to measure and control the total water usage in the supply chain in order to enhance sustainability. The water requirements for each activity in supply chain are tabulated in Table 6.7.

Table 6.7: Water consumption rate for each activity.

SCM Activities	Water Requirement [m^3/t biomass]	Reference
DLF/Energy Pack Production	0.00	-
Gasification	0.1380	(Lampert et al., 2015)
Pyrolysis (Fast and slow)	0.0231[a]	(Hsu, 2011)
Bio-ethanol Production (Fermentation)	0.1489[b]	(Kumar & Murthy, 2011)
	0.1510[c]	
	0.1685[d]	
	0.1154[e]	
Citric Acid Production	0.0214	(James & Currie, 1917)
Biogas-energy generation[f]	0.00	(EPA, 1998)
Transportation [g/L fuel]	0.00	-
Importing energy [m^3/kWh]	7.20 E-05	(Pikoń, 2012)
Combustion [m^3/kWh]	1.80 E-05	(Pikoń, 2012)

[a] Assume density of bio-oil is 1170 g/L (Gansekoele, 2016).
[b] Undergo dilute acid pre-treatment. [c] Undergo dilute alkaline pre-treatment.
[d] Undergo hot water pre-treatment. [e] Undergo steam explosion pre-treatment.

6.6.5 Land use

In this work, LF only consider the built-up land footprint (i.e., the additional land areas required to set up the processing hubs), while the crop land footprint (i.e., the land areas required to produce crop) is not considered. This is because all the biomass considered in this work are crop residues and process wastes. The utilisation of crop land is not originally aimed to generate biomass but to provide food (e.g., paddy field is aimed to produce rice). It is assumed that 20,000 m^2 of land area is required per processing hub (see Equation (6.15)).

6.6.6 Other required data

The electricity required for each technology is listed in Chapter 4 (see Table 4.3). Besides, the production of biomass-based fuels or energy can be used to substitute the fossil-based energy. Table 6.8 shows the energy content of each biomass-based fuel.

Table 6.8: Energy content of bio-fuel products.

Products	Energy [MJ/L]	Reference
Energy Pack [MJ/kg]	21.00	(Ng et al., 2014)
Bio-oil	21.60	(Steele et al., 2012)
Syngas[d] [MJ/m^3]	19.57[a]	(Capareda, 2014)
	20.29[b]	
	10.94[c]	-
Bio-ethanol	21.00	(BEC, 2011)
Coal [MJ/kg]	29.30	(Smil, 2008)

[a] Fast pyrolysis under 500 °C
[b] Slow pyrolysis under 400 °C
[c] Gasification of EFB under 600 °C
[d] Syngas-to-electricity efficiency is assumed at 38 % (Kreith & Krumdieck, 2014)

6.7 Result and Discussion

6.7.1 *s*-vector

The *s*-vectors for each conversion process are presented in Figure 6.8 to Figure 6.11, while the data is tabulated in Table 6.9. The results show that most of the bioenergy products such as energy pack, py-oil, bio-ethanol is more preferred (fall on the first quadrant). This suggests that these processes will not only provide extensive revenue, but will also reduce the environmental impacts. With the production of these bio-fuels, the requirement of fossil-based fuels is substantially reduced. However, biomass combustion and anaerobic digestion that generates electricity poses a different situation. These technologies fall on the second quadrant ($270^o > \theta > 90^o$) which indicates the presence of negative profit. This is probably due to the unattractive tariff (SEDA, 2017), unsupportive incentive policy (Ahmad et al., 2011) and low boiler efficiency (MIGHT, 2013).

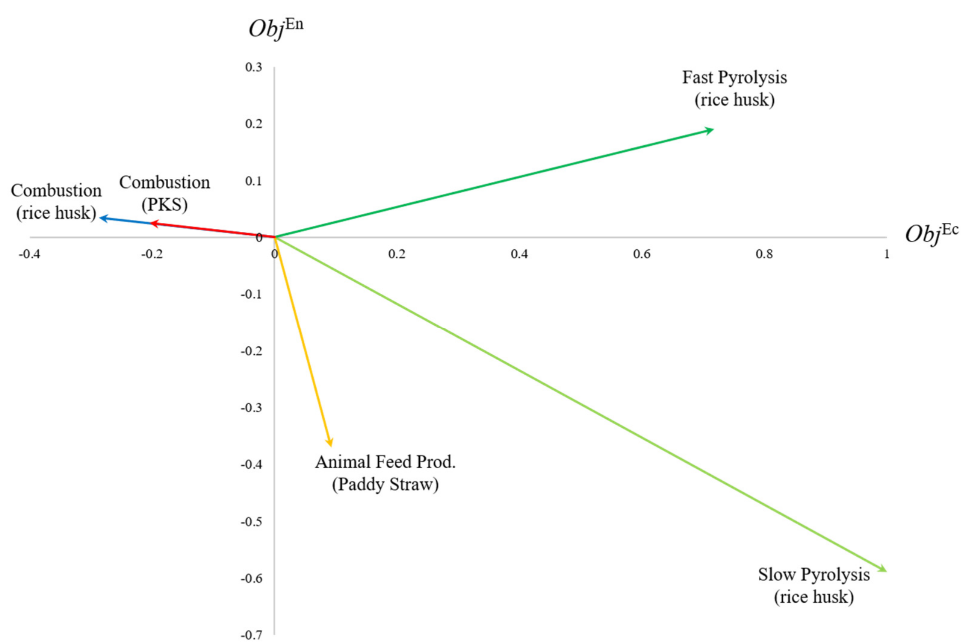

Figure 6.8: *s*-vector of each conversion process for paddy biomass.

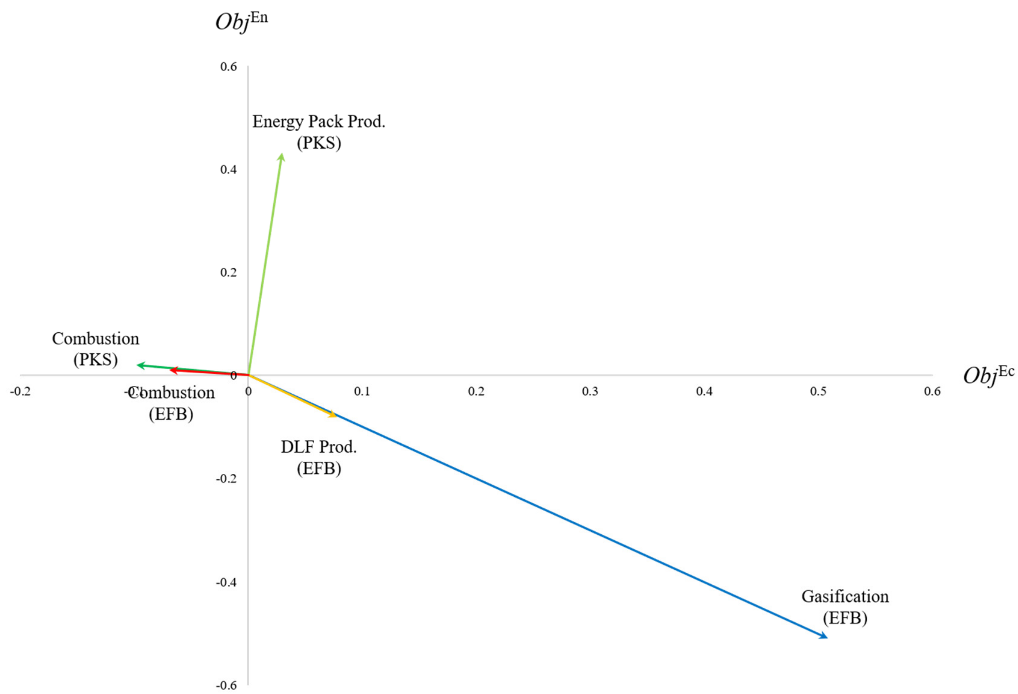

Figure 6.9: s-vector of each conversion process for palm oil biomass.

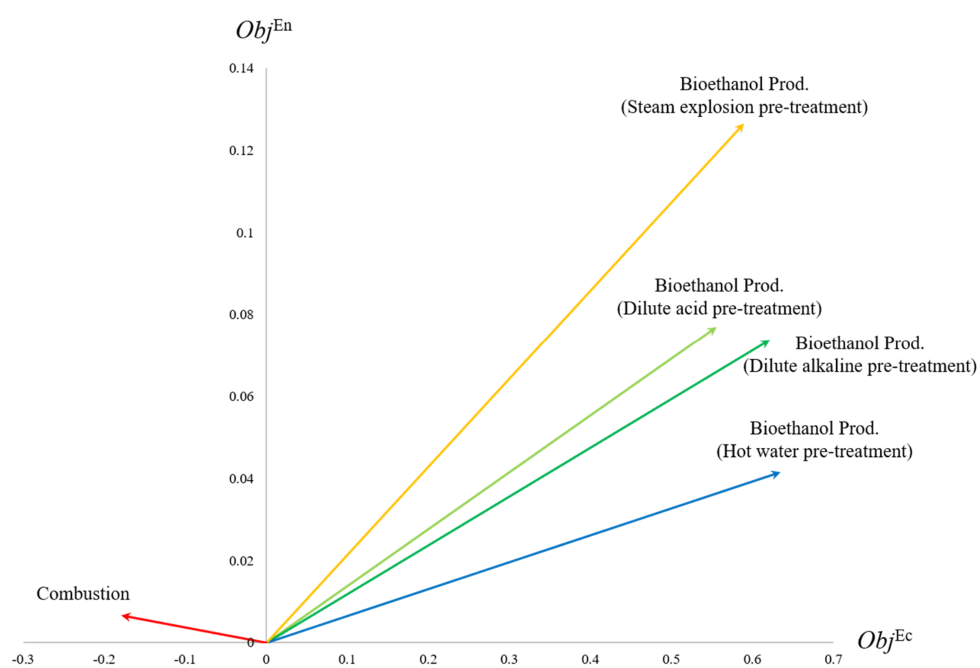

Figure 6.10: s-vector of each conversion process for sugarcane bagasse.

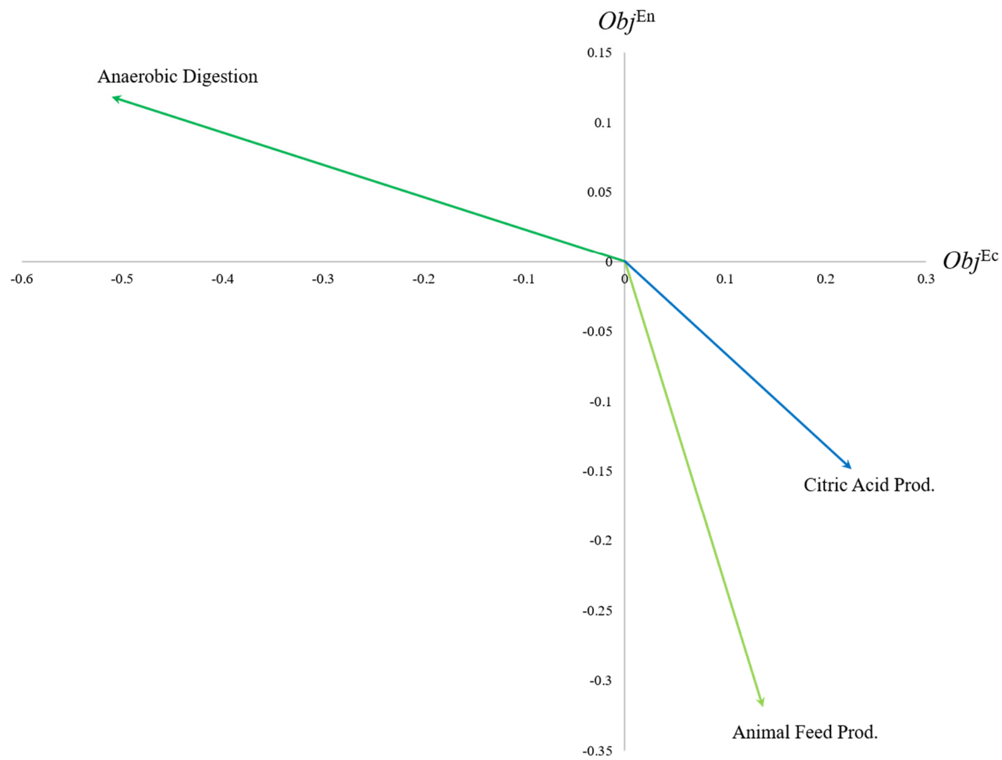

Figure 6.11: *s*-vector of each conversion process for pineapple peel.

Table 6.9: s-vector data for each process.

No.	**Description**	Mag_n	θ_n (°)	λ^{Ec*}	λ^{En*}
Paddy Biomass					
1	Rice Husk → Slow Pyrolysis	1.1603	329.52	1.000	0.4482
2	Rice Husk → Fast Pyrolysis	0.7425	14.82	0.8132	0.7186
3	Rice Husk → Combustion	0.2891	173.10	0.1481	0.6647
4	Paddy Straw → Animal Feed Prod.	0.3821	284.08	0.3996	0.5239
5	Paddy Straw → Combustion	0.2061	172.79	0.2028	0.6616
Palm Oil Biomass					
1	EFB → Gasification	0.7190	314.99	0.6745	0.4760

Table 6.9(cont'): s-vector data for each process.

No.	Description	Mag_n	θ_n (°)	λ^{Ec*}	λ^{En*}
Palm Oil Biomass					
2	EFB → DLF Prod.	0.1123	314.99	0.3896	0.6245
3	EFB → Combustion	0.0700	172.13	0.2922	0.6560
4	PKS → Energy Pack Prod.	0.4334	86.13	0.3575	0.8028
5	PKS → Combustion	0.1002	168.66	0.2731	0.6595
Sugarcane Bagasse					
1	Sugarcane Bagasse → Bioethanol Prod. (Dilute-acid Pre-treatment)	0.5611	7.88	0.7060	0.6793
2	Sugarcane Bagasse → Bioethanol Prod. (Dilute-alkaline Pre-treatment)	0.6262	6.78	0.7497	0.6783
3	Sugarcane Bagasse → Bioethanol Prod. (Hot Water Pre-treatment)	0.6363	3.74	0.7584	0.6670
4	Sugarcane Bagasse → Bioethanol Prod. (Steam Explosion Pre-treatment)	0.6029	12.11	0.7283	0.6966
5	Sugarcane Bagasse → Combustion	0.1793	177.86	0.2195	0.6550
Pineapple Peel					
1	Pineapple Peel → Citric Acid Prod.	0.2703	326.70	0.4876	0.6011
2	Pineapple Peel → Animal Feed Prod.	0.3476	293.30	0.4291	0.5417
3	Pineapple Peel → Anaerobic Digestion	0.5244	166.93	0.000	0.6938
Reference					
1	$\lambda^{Ec(Ref)}$	0.3381			
2	$\lambda^{En(Ref)}$	0.6526			

* value obtained by assuming 1 t of each biomass type is used.

6.7.2 Pareto analysis

The proposed model is further analysed by conducting a Pareto analysis. More than 500 solutions are obtained and tabulated accordingly in Figure 6.12. The figure shows that six clusters of solutions (close to each other) are formed. The closer view of these cluster solutions is presented in the red box. Green dots represent all the combinatorial solutions, where the optimal solutions are presented in darker colour. These optimal solutions are obtained from the mathematical model formulated in Section 6.4. To achieve this, different sets of priority scale are used to optimise the weighted sum optimisation model. Table 6.10 tabulates the boundary data used obtained from the model (i.e., the upper and lower limit of the model). Note that not all environmental indicators show the same pattern when compared to the cost (Pareto analysis of GWP, AP and ADP follow Pattern A; POCP follows Pattern B; remaining follow Pattern C). This indicates that the relative importance (weightage) assigned to the impact category is a critical factor that will affect the obtained optimal solution.

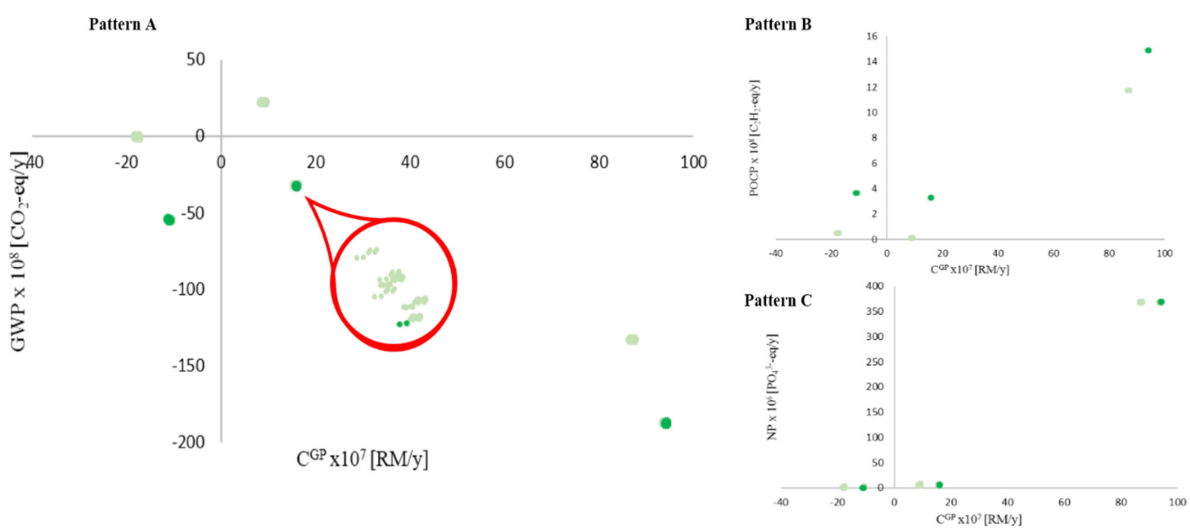

Figure 6.12: Pareto studies.

Table 6.10: Boundary data.

Indicators	Max	Min
$\boldsymbol{C}^{\mathbf{GP}}$ [RM/y]	9.42×10^{8}	-1.81×10^{8}
GWP [t-eq/y]	2.23×10^{9}	-1.90×10^{10}
AP [t-eq/y]	1.76×10^{7}	-1.60×10^{8}
POCP [t-eq/y]	1.49×10^{9}	0
NP [t-eq/y]	3.70×10^{8}	0
ATP [t-eq/y]	6.32×10^{9}	-23.04
TTP [t-eq/y]	1.25×10^{8}	-6.72
ADP [t-eq/y]	1.29×10^{6}	-1.20×10^{7}
WF [m^3/y]	4.96×10^{5}	0
LF [m^2]	2.20 x 105	0

Different sets of priority scale are assigned to the objectives to investigate the effect of the priority scale on the optimal solutions (please refer Appendix Section A.3 for the model coding and result). The results are summarised in Figure 6.13. To illustrate, by reducing the priority scale for economic performance from 67 % to 52 %, pineapple peel will be processed into animal feed instead of converting into citric acid. As a result, the overall profit has become 0.016 % lower (equivalent to RM 151,865/y), while the overall GWP is mitigated (i.e., 0.008 % lesser, equivalent to 1.514 MtCO2-eq/y). Moreover, under low priority scale for economic performance, the optimal number of hubs has switched to four in order to reduce the carbon emission through transportation, in spite of the higher investment cost for the hubs. The result shows that the optimal solution obtained from the model is very sensitive to the priority scale input to the model. This suggests that collaborative stakeholder engagement is very important, in order to prevent mismatch expectation between stakeholders and reduce unnecessary investment (NEPCon, 2016).

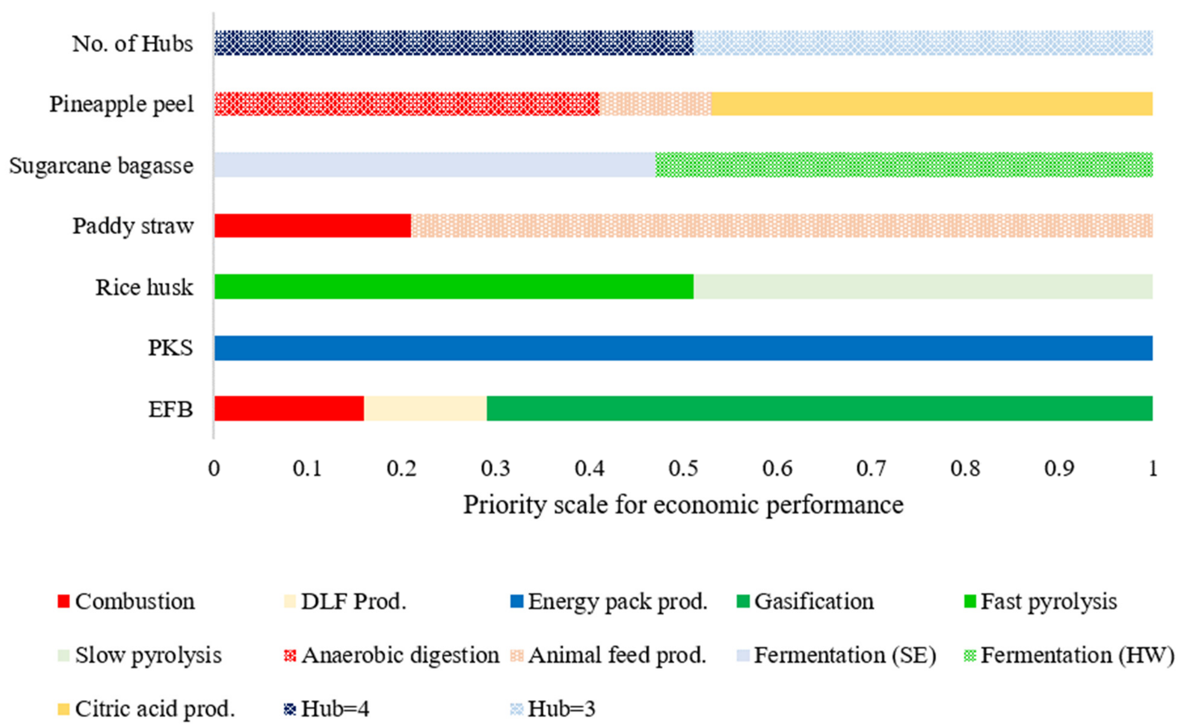

Figure 6.13: Technology and hub selection at different priority scale.

6.7.3 Limitation of the approach/ *s*-vector

Despite the proposed approach is applicable for a large-scale multi-biomass supply chain problem (industrial complex level), there are rooms for improvement. The key limitation of this approach is the low traceability of the result. The model determines the economic and environmental sustainability by accounting several variables by using a weighted sum model. The forward computation is simply straightforward, but the reverse calculation poses a different story. For instance, given the final outcome P is a function of a set of variables, while a set of weightages is assigned to the variable. Then, P can be determined by multiplying the variables to its assigned weightage. However, it is nearly impossible to back-estimate the exact value of the variables from the P (see Figure 6.14). In other words, it is very difficult to identify what had gone wrong (or what should be fixed) merely based on the final score (e.g., λ^{En}), which is a function of several variables (e.g., GWP).

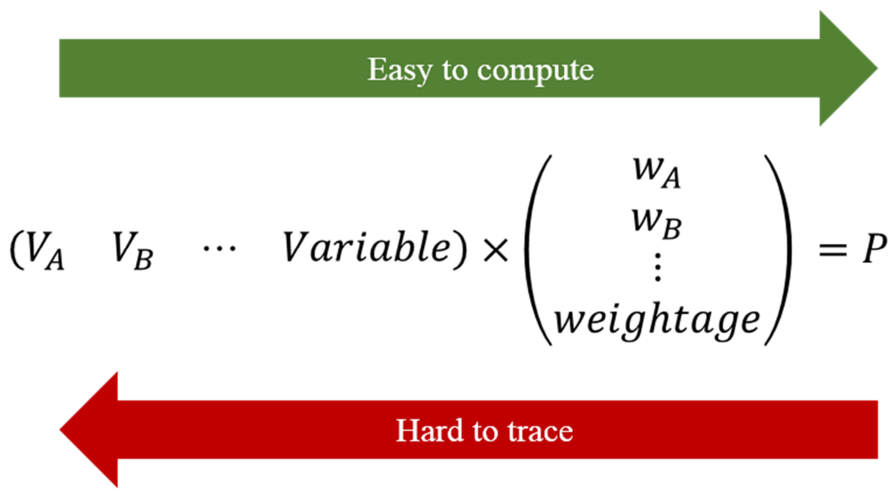

Figure 6.14: Illustration of the limitation.

In addition, the final sustainability scoring for the supply chain is highly dependent on the priority scale assigned to the model. Hence, lowering down the overall comparability of the results. For instance, assume two users (1 and 2) are evaluating a similar technology by using different sets of priority scale. Both user will obtain different scores for a same technology, causing misunderstanding and confusion among users. Therefore, in order to make the results become comparable to each other, same set of priority scale has to be used.

Furthermore, the robustness of the model is another key concern of this approach. In this work, data is obtained from various sources (in diferent location). Since different practice (operational, evaluation, etc.) is opted in different places, the reliability of the obtained data might be uncertain. Therefore, in order to enhance the reliability of the results, the obtained data should be benchmarked and analysed before utilised. On top of that, despite most of the impact categories have been covered in this approach, there are still some other indexes that are considered in other environmental assessment tool, are omitted. Thus, by integrating different environmental assessment tools (e.g., LCA, Eco-indicator 99, etc.) into the model, the obtained results might be different. The reviews on these omitted indexes are tabulated in Table 6.11.

Table 6.11: Some of the omitted environmental indicators.

Indicators	Description
Mineral resources requirement (considered in LCA)	Some tools consider the uptake of mineral resources for the equipment fabrication, processing hub construction, transport manufacture, etc. However, in this pioneering stage of biomass industry in Malaysia, most of this data still remains uncertain, causing low reliability of results.
Agricultural land-use (considered in Eco-indicators 99)	The agriculture land-use is not considered in the model as all biomass considered in this work are crop residues and process wastes. The agricultural land-use is not originally aimed for biomass harvesting but for food production. However, this indicator should be considered when the biomass industry is commercialised, as additional land is required to harvest biomass in order to cope with the increasing biomass demand.
Human toxicity (considered in Eco-indicators 99, IMPACT 2002+, WAR, etc.)	In most of the environmental assessment tools, human toxicity index is placed under environmental indicators. However, human toxicity indexes such as HTPI and HTPE are more related to safety concerns. Thus, these indexes are categorised as social indicators in this work.

6.8 Conclusion

This chapter has synthesised an integrated biomass supply chain with the consideration of both economic and environmental sustainability. The main contributions are sated below:

I. The mathematical model proposed in previous chapter is reworked to consider several environmental impacts in the supply chain model.

II. Sustainable-vector (*s*-vector) is proposed to demonstrate how the results perform based on the satisfaction on economic and environmental sustainability.

III. Pareto study is conducted to analyse the effect of relative priority of each objective on the technology selection and optimal number of hubs.

IV. Limitation of the proposed approach is discussed in order identify the potential room of improvement.

Even though important aspects have been studied in this chapter, there are still several extension-works have to be done. Firstly, the model should be extended to consider social impacts of the supply chain (e.g., safety index, job creation, etc.) in order to cover the whole spectrum of sustainability. Aside from this, model adjustment should be made to increase the traceability and comparability of the results. Moreover, since the data used in this work is obtained from various sources (different location), the reliability of the obtained results might be uncertain (due to different operation practice, different biomass quality, etc.). In order to address this issue, benchmarking of data should be carried out. In addition, the proposed model can be extended into broader framework to plan for debottlenecking for the biomass industry in Malaysia.

Chapter 7:

Sustainable Evaluation for Biomass Supply Chain:

Novel PCA Aided Optimisation Approach

7.1 Introduction

Due to the growing consumer awareness and snowballing pressure from the communities and NGOs, the concept of incorporating all three dimensions of sustainability (i.e., economic, environmental and social) has played an important role in SCM of the 21st century (Chardine-Baumann & Botta-Genoulaz, 2014). Although both economic and environmental sustainability have received the greatest amount of interest from both academicians and industry practitioners, social sustainability has seen less attention. Therefore, in this chapter, the final piece of sustainability dimension is considered in the formulated model. Social issues including health and safety aspects in the processing hubs, job creation and transportation safety are managed in a way that ensures long-term survivability of the entire supply chain business. In this case, the sustainability performance of a supply chain is compounded of a complex series of variables. This might lead to redundancies in variables that further make the outcomes become less readable (Shlens, 2003).

In order to address this issue, Principal Component Analysis (PCA) is introduced to remove he complexity and redundancy of the data series. In short, PCA is a powerful multivariate statistical technique that allows converting a series of correlated variables into a set of uncorrelated variables known as principal components (PCs), without losing too much information (Aitchison, 1983). This technique has been used abundantly in various forms of study, including image compression (Dash et al., 2014), chemical plant design (Pozo et al., 2012) and biomass properties analysis (Jenkins et al., 1998). However, to date, PCA approach has not been applied to optimise the sustainability performance of the biomass supply chain.

In this chapter, a novel systematic optimisation approach that incorporates PCA and AHP is proposed to determine the optimal technology selection and optimal transportation design for an integrated biomass supply chain. A similar case study in Johor is used to demonstrate the effectiveness of the proposed method. Aside from this, the obtained optimised results are compared and benchmarked with the results obtained from other conventional optimisation approaches. This chapter is organised as follows: A formal problem statement of this work is structured in section 7.2. Section 7.3 outlines the research method used for this proposed problem. This lays the foundation for section 7.4, which introduces the modified mathematical model. In section 7.5, the same case study is used to demonstrate the applicability of the proposed method. It is followed by the result and discussion in Section 7.6. Finally, conclusion and future research are given towards the end of the chapter.

7.2 Problem Statement

The problem described in this chapter aim to determine the optimal technology selection and optimal transportation design for an integrated biomass supply chain that maximise the annual profit and social benefits while keeping the environmental impacts at minimal. It is formally stated as follows: given a set of biomass types r supplied from a set of sources i is delivered through a set of transportation modes m to a set of processing hubs j. Then, it is converted into a set of intermediates l and a set of products p via a set of technologies t and t'. Finally, products p will be delivered to a set of customers k through a set of transportation mode m'. Throughout the entire supply chain, a set of pollutants a is released to the environment and cause a set of environmental issues q; at the same time, these activities will lead to a set of social impacts u. The generic superstructure of the modified model is shown in Figure 7.1.

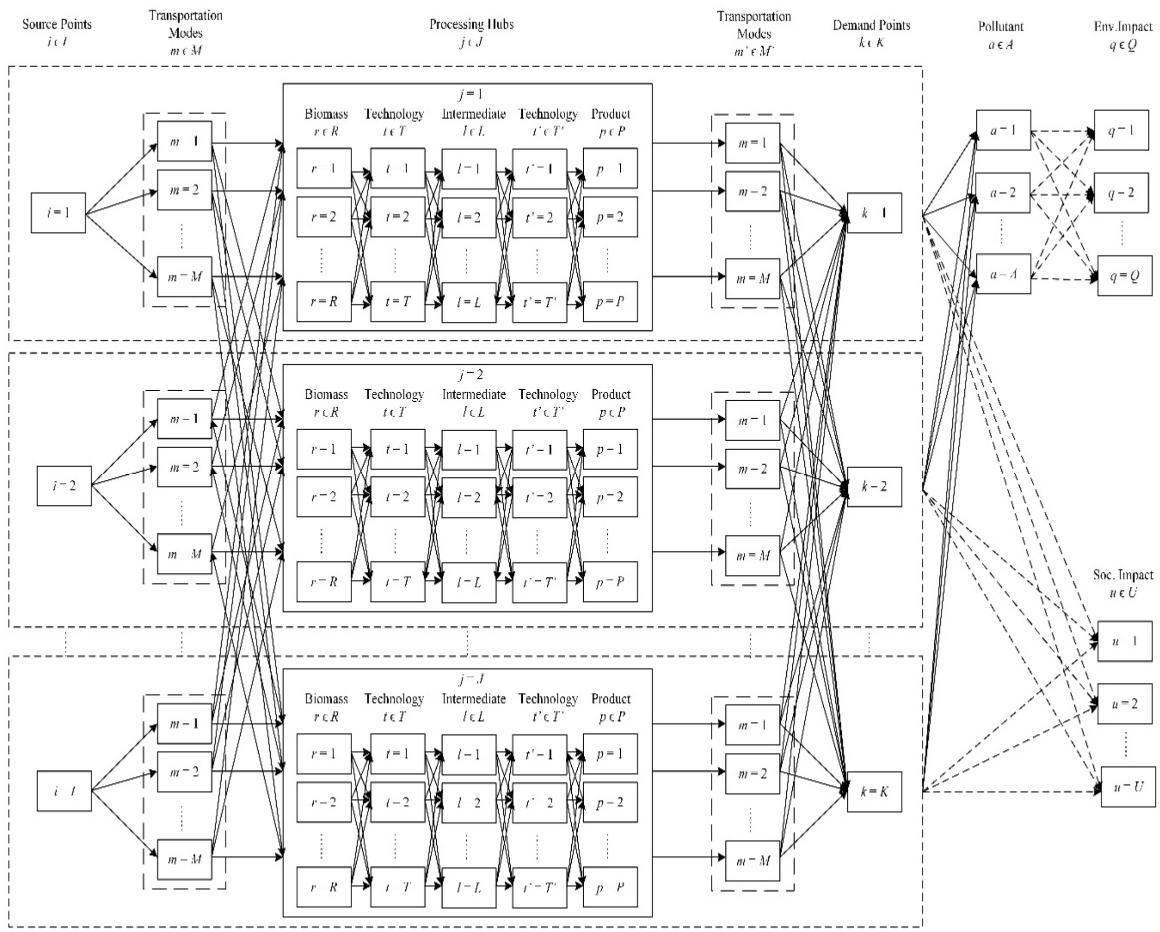

Figure 7.1: Generic superstructure of the proposed model (modified from Figure 6.1).

7.3 Methodology

The sustainability performances (economic, environmnetal and social dimensions) of each possible solution is determined by using the formulated model and is analysed through PCA in order to remove the redundancy. In this work, the technology selection and transportation design are optimised based on the PCs score. However, the optimisation based on PCs scores is not that straight forward, as PCs encompass of convex combinations of original variables (Pozo et al., 2012). Therefore, this work proposes a systematic optimisation approach which utilised analytical hierarchy process (AHP) to assign relative priority scale to the contradicting objectives, helping decision-makers to decide whether the correspond PCs should be maximised or minimised. Note that the description of AHP technique is given in Section 7.4.3). Finally, the optimised results are compared with two other conventional optimisation approaches. Figure 7.2 presents the research method used in this work. The detailed formulations are given in the next section.

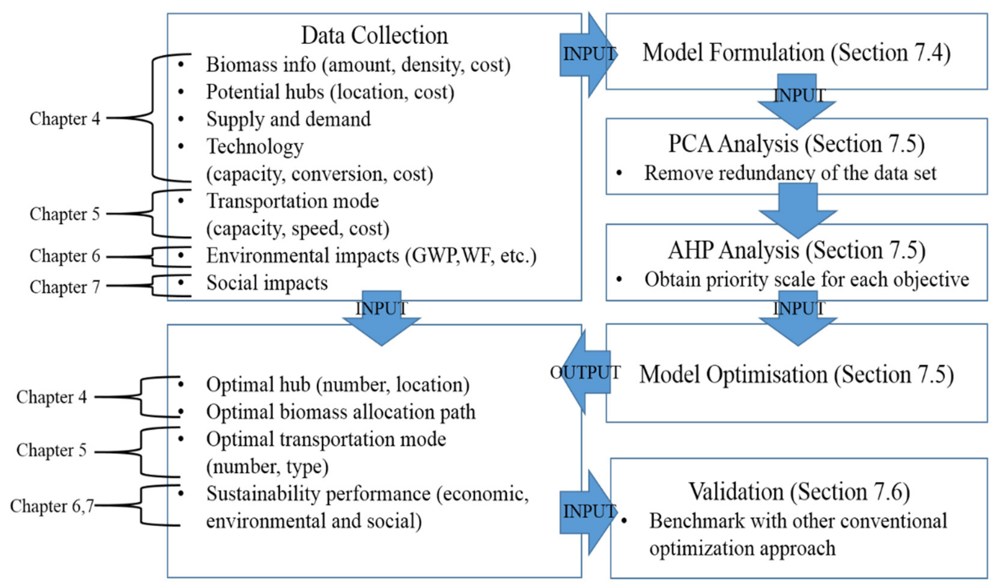

Figure 7.2: Overview of research method for Chapter 7 (reproduced from Figure 3.4).

7.4 Model Formulation

The model formulated in Chapter 6 is revised to consider various social concerns in the model. The problem is modelled through Mixed integers linear programming (MILP) and will be solved by using Lingo v14.0 (Lingo, 2015). It is formulated according to the subsections below:

7.4.1 Economic and environmental performances

The evaluations of economic and environmental performances for this work are adapted from the previous chapter. Please refer to Chapter 6 for the detailed descriptions and calculations.

7.4.2 Social performance

Regular monitoring on social sustainability is essential to enhance long-term survivability of a company as well as to attain sustainable societal lifestyles (Klemeš et al., 2012). Therefore, social issues including health and safety aspects in the processing hubs, transportation safety and job creation are considered in the social evaluation. The detailed description of each aspect is presented in subsections below:

7.4.2.1 Human toxicity potential

In this work, human toxicity potential (i.e., human toxicity potential by ingestion (HTPI) and human toxicity potential by either inhalation or dermal exposure (HTPE)) is used as the health indicator in this model. In general, HTPE is measured for a chemical if it is existed as gaseous state at 0 ^{o}C and under atmospheric pressure; while HTPI were calculated for a chemical if it is existed as a liquid or solid under these conditions (Young & Cabezas, 1999). Same as the calculation of environmental impact EI_q [t-eq/y], the social impact SI_u [t-eq/y] in terms of human toxicity potential is measured throughout the entire supply chain:

$$SI_u = SI_u^{\text{Process}} + SI_u^{\text{Prod}} + SI_u^{\text{Elec}} + SI_u^{\text{Tr}} \qquad \forall u \in U \tag{7.1}$$

where SI_u^{Process} refers to the social impact in terms of human toxicity potential due to the pollutant emitted from the conversion process; SI_u^{Prod} refers to the social impact in terms of human toxicity potential due to the product; SI_u^{Elec} refers to the social impact in terms of human toxicity potential due to the energy consumption in the hub; SI_u^{Tr} refers to the social impact in terms of human toxicity potential due to the fuel consumption during transportation of biomass *r* and product *p*.

SI_u^{Process} can be determine by accounting the social impacts in terms of human toxicity potential of each pollutant *a* which are emitted from the conversion process in the processing hub *j*. It is expressed as:

$$SI_u^{\text{Process}} = \sum_a (F_a \times \Psi_{a,u}) \qquad \forall u \in U \tag{7.2}$$

where F_a [t/y] refers to the total emission rate of the pollutants *a*, emitted to the aquatic, terrestrial and atmospheric environment during the conversion process in the processing hub *j*; while $\Psi_{a,u}$ [t-eq/t] refers to the score of social impact of pollutant *a* in terms of human toxicity potential.

Similarly to EI_q^{Prod}, SI_u^{Prod} also concerns on both of the direct effect, $SI_u^{\text{Prod\_Direct}}$ [t-eq/y] (burdening effect) and indirect effect, $SI_u^{\text{Prod\_Indirect}}$ (unburdening effect) on the social impact in terms of human toxicity potential.

$$SI_u^{\text{Prod}} = SI_u^{\text{Prod\_Direct}} + SI_u^{\text{Prod\_Indirect}} \qquad \forall u \in U \qquad (7.3)$$

$SI_u^{\text{Prod\_Direct}}$ is determined by multiplying the product flow in hub j to the score of social impact caused by production in terms of human toxicity potential, $\Psi_{p,u}$.

$$SI_u^{\text{Prod\_Direct}} = \sum_p (\sum_j F_{p,j} \times \Psi_{p,u}) \times \text{OPD} \qquad \forall u \in U \qquad (7.4)$$

Indirect effect of a product refers to the unburdening effect caused by the substitution of conventional non-renewable fossil energy with the biomass-based energy. It is defined in Equation (7.5), where Ψ_u^{Fossil} refers to the score of social impact caused by the utilisation of fossil-based energy in terms of human toxicity potential. Note that the negative sign of $SI_u^{\text{Prod\_Indirect}}$ indicates that the substitution of fossil-based fuel is beneficial to the social.

$$SI_u^{\text{Prod\_Indirect}} = -F^{\text{FossilFuel\_Sub}} \times \Psi_u^{\text{Fossil}} \qquad \forall u \in U \qquad (7.5)$$

SI_u^{Elec} considers the social impact which attributed by imported energy and the self-generated bio-electricity. It can be determined by using Equation (7.6).

$$SI_u^{\text{Elec}} = (Elec^{\text{Imp}} - Elec^{\text{Gen}}) \times \Psi_u^{\text{Fossil}} \qquad \forall u \in U \qquad (7.6)$$

SI_u^{Tr} considers the social impact in terms of human toxicity potential which attributed to the fuel consumption during transportation. It is expressed as follow:

$$SI_u^{\mathrm{Tr}} = F^{\mathrm{Fuel}} \times \Psi_u^{\mathrm{Fossil}} \qquad \forall u \in U \tag{7.7}$$

Similar to the calculation for TTP, the lethal-dose that caused death of 50 % of rats by oral ingestion (LD50) is used as an estimation for HTPI as well. In general, higher LD_{50} indicates a lower toxicity of the respective chemical:

$$\Psi_{u=HTPI} = \frac{1}{\mathrm{LD}_{50}} \tag{7.8}$$

where $\Psi_{u=HTPI}$ [kg/mg] refers to the social impact in terms of human toxicity potential by ingestion. In other hand, HTPE is estimated from time-weighted averages of threshold limit values ($\mathrm{TLV}^{\mathrm{TWA}}$ [ppm]). It shows the occupational exposure limits of a chemical substance over the course of an eight hours work shift. This value is generally issued by the American Conference of Governmental Industrial Hygienists (ACGIH) and Occupational Safety and Health Administration (OSHA). It is chosen because of its prevalence in the literature and wide acceptance by most of the countries.

$$\Psi_{u=HTPE} = \frac{1}{\mathrm{TLV}^{\mathrm{TWA}}} \tag{7.9}$$

where $\Psi_{u=HTPE}$ [ppm^{-1}] refers to the social impact in terms of human toxicity potential by inhalation and dermal exposure. Note that the score for both HTPE and HTPI are obtained from the WAR algorithm software (WAR GUI, 2011) developed by the U.S. Environmental Protection Agency.

7.4.2.2 Inherent safety in processing hub

The safety aspect of the processing hub is evaluated by using Inherent Safety Index (ISI) which introduced by Hurme and Heikkilä (1998). The total inherent safety index for process *n*, I_n^{TI} contains of two major components, i.e., chemical inherent safety for process *n*, I_n^{CI} and process inherent safety, I_n^{PI} for process *n*:

$$I_n^{\mathrm{TI}} = I_n^{\mathrm{CI}} + I_n^{\mathrm{PI}} \qquad \forall n \in N \qquad (7.10)$$

$\mathrm{I}_n^{\mathrm{CI}}$ concerns on several chemical factors, including factor for heat of main reaction, $\mathrm{I}_n^{\mathrm{RM,ax}}$; heat of side reaction, $I_n^{\mathrm{RS,Max}}$; chemical interaction, $I_n^{INT,Max}$; flammability, I_n^{FL}; explosiveness, I_n^{EX}; toxic exposure, I_n^{TOX}; and chemical corrosiveness, $I_n^{\mathrm{COR,Max}}$:

$$I_n^{\mathrm{CI}} = I_n^{\mathrm{RM,Max}} + I_n^{\mathrm{RS,Max}} + I_n^{\mathrm{INT,Max}} + (I_n^{\mathrm{FL}} + I_n^{\mathrm{EX}} + I_n^{\mathrm{TOX}})^{\mathrm{Max}} + I_n^{\mathrm{COR,Max}} \qquad \forall n \in N \qquad (7.11)$$

$\mathrm{I}_n^{\mathrm{PI}}$ expresses the inherent safety of the process. It contains of factor for process inventory, $\mathrm{I}_n^{\mathrm{Inv}}$; process temperature, $\mathrm{I}_n^{\mathrm{Temp}}$; process pressure, $\mathrm{I}_n^{\mathrm{Press}}$; equipment safety, $\mathrm{I}_n^{\mathrm{ES,Max}}$; and safe process structure, $\mathrm{I}_n^{\mathrm{ST,Max}}$.

$$\mathrm{I}_n^{\mathrm{PI}} = \mathrm{I}_n^{\mathrm{Inv}} + I_n^{\mathrm{Temp}} + I_n^{\mathrm{Press}} + I_n^{\mathrm{ES,Max}} + I_n^{\mathrm{ST,Max}} \qquad \forall n \in N \qquad (7.12)$$

All the calculations for these indices are based on worst-case scenario. For instance, the greatest sum for flammability, explosiveness and toxic exposure indices is used during the calculation. The overall ISI for the synthesised biomass supply chain is defined in Equation (7.13). Note that a low value of ISI indicates an inherently safer biomass supply chain.

$$ISI = \sum_n \mathrm{I}_n^{\mathrm{TI}} \tag{7.13}$$

7.4.2.3 Transportation safety

Driving speed is the major factor that contributes to accidents. A research from the Road Accident Research Unit in University of Adelaide shows that a small change in speed can result in a significant reduction in road accident (e.g., a 5 km/h reduction in driving speed can lead to at least 15 % decrease in accident) (Transport Accident Commission, 2012). Therefore, speeding driver is more likely to crash compared to other drivers that are travelling at lower speed. In this work, the relationship between impact speed, $\mathrm{Sp}_m^{\mathrm{Impact}}$ [km/h] and the risk of pedestrian fatality, ${\mathrm{P}_m}^{\mathrm{Fatality}}$ [%] which is found by Rosén and Sander (2009), are used to measure the road safety. The sample used in that research included pedestrian impacts occurring between 1999 and 2007. The relationship is defined as:

$${\mathrm{P}_m}^{\mathrm{Fatality}} = \frac{1}{1+e^{6.9-0.090\,\mathrm{Sp}_m^{\mathrm{Impact}}}} \qquad \forall m \in M \tag{7.14}$$

7.4.2.4 Job creation

Literatures have proven that several social benefits will arise from job creation, e.g., having a job will help individuals stay connected with society, build self-esteem, develop communication skills and create competencies. The social impact in terms of job creation, JC [jobs] assesses the job vacancies created by the entire supply chain, starting from the suppliers to the final product distributors. This includes direct jobs,

JC_n^{Direct}[jobs] which refer to the employment directly related to the production of biomass-based products (i.e., operators, engineers, etc.) and indirect jobs, JC_n^{Indirect} [jobs] which refer to the jobs created outside the regional center commercial enterprise (i.e., suppliers, collectors, etc.). It is estimated based on the regional statistics (see Section 7.5.1.4):

$$JC = \sum_n (JC_n^{\text{Direct}} + JC_n^{\text{Indirect}}) \tag{7.15}$$

7.4.3 Analytical hierarchy process (AHP)

In order to determine the relative priority scale for each objective in a more systematic way, analytical hierarchy process (AHP) is introduced. AHP is a theory of measurement through pairwise comparisons and relies on the expert's judgements to derive priority scales (Saaty, 2008). In general, AHP is used to decompose the decision into 6 steps:

I. **Define the goal of the work**: Ensure the objective of the problem is specified. In this case, developing a sustainable biomass supply chain is the ultimate goal.

II. **Construct the decision hierarchy**: Involve of criteria analysis and identification. The decision hierarchy start from the top level with the goal of the work (i.e., Development of sustainable supply chain), followed by the intermediate level which define the criteria (i.e., sustainability dimensions) and sub-criteria (i.e., different types of environmental impact), to the lowest level (i.e., a set of process alternatives). The criteria and sub-criteria are prioritised based on their level. Figure 7.3 shows the general hierarchy structure.

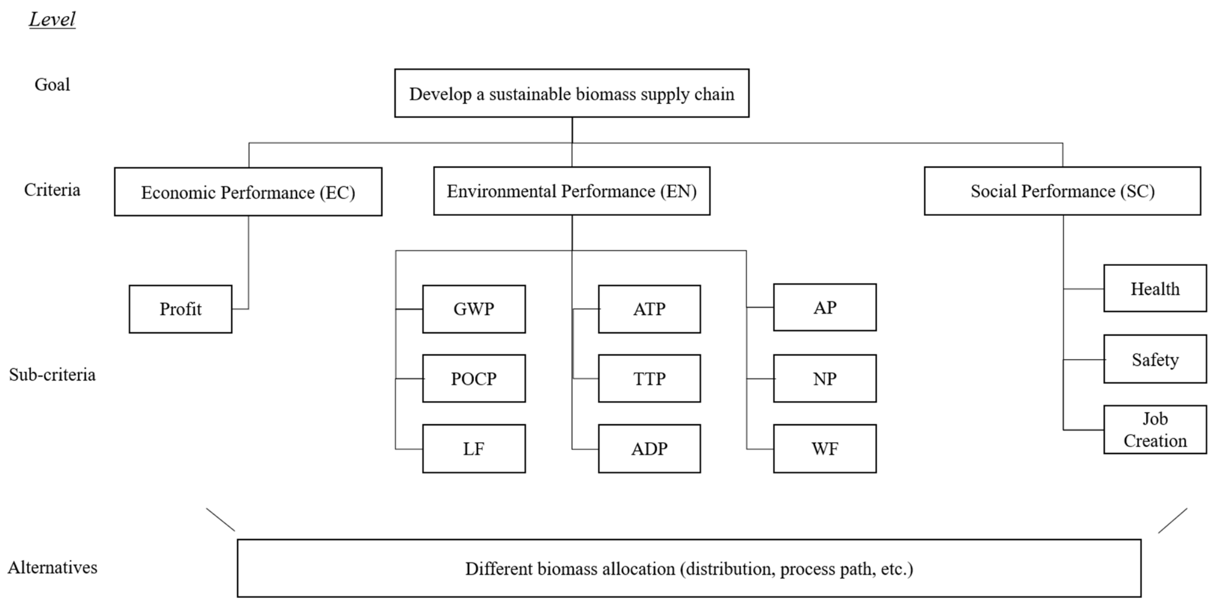

Figure 7.3: Hierarchical structure for sustainable biomass supply chain development.

III. **Construct pairwise comparison matrices for each level**: Pairwise comparison matrices for each level of criteria and sub-criteria is constructed based on the expert judgement. It is constructed according to the relative importance of each criterion. Table 7.1 represents the general structure of a pairwise comparison matrix, where C_1, C_2 … C_n refer to the criteria, while c_{11}, c_{12}, … c_{nn} refer to the numerical comparison scale that assign to each criterion (note that c_{12} indicates the numerical comparison scale that assign to C_1 relative to C_2). These numerical comparison scale are attained through a nine-point Saaty's scale as shown in Table 7.2.

Table 7.1: General structure of pairwise comparison matrix.

	C_1	C_2	…	C_n
C_1	c_{11}	c_{12}	…	c_{1n}
C_2	c_{21}	c_{22}	…	c_{2n}
⋮	⋮	⋮	⋮	⋮
C_n	c_{n1}	c_{n2}	…	c_{nn}

Table 7.2: Numerical comparison scale (Saaty, 1977).

Intensity of importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one criterion over another
5	Strong importance	Experience and judgement strongly favour one criterion over another
7	Very strong importance	A criterion is favoured very strongly over another, its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one criterion over another is of the highest possible order of affirmation
2, 4, 6, 8	Used when compromise between values of 1, 3, 5, 7, 9 is needed	

IV. **Computation of the priority scale**: Eigenvalues and eigenvector of the pairwise comparison matrix is obtained in order to determine the relative importance of each criterion. Let the $n \times n$ comparison matrix in Table 7.1 be matrix $\boldsymbol{A}$:

$$\boldsymbol{A} = \begin{bmatrix} c_{11} & \cdots & c_{1n} \\ \vdots & \ddots & \vdots \\ c_{n1} & \cdots & c_{nn} \end{bmatrix} \tag{7.16}$$

$$\boldsymbol{Aw} = \lambda^{\text{Max}}\boldsymbol{w} \tag{7.17}$$

$$\boldsymbol{w} = \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} \tag{7.18}$$

where, $\boldsymbol{w}$ is the eigenvector which represents the weightage or priority of each criterion $(\text{i.e.}, w_1, \ldots w_n)$, while λ^{Max} refers to the eigenvalue of the pairwise comparison matrix. The eigenvector can be determined through a simple method: Firstly, all cells in an individual column are summed together. Then, this value is divided with the sum of all cells in the comparison matrix. Repeat these steps in all rows, the result is the eigenvector $\boldsymbol{w}$. After obtaining the eigenvector, the λ^{Max} can be obtained by dividing the cell in n^{th} row of matrix $\boldsymbol{Aw}$ by the cell in n^{th} row of matrix $\boldsymbol{w}$. The value should be same for each row.

V. **Check the consistency ratio**: The consistency of the pairwise comparison can be analysed through the consistency ratio (CR). It is defined as follow:

$$CR = \frac{CI}{\text{RI}} \tag{7.19}$$

$$CI = \frac{\lambda^{\text{Max}} - \text{n}}{\text{n} - 1} \tag{7.20}$$

where CI refers to the consistency index which can be determined by using Equation (7.19), while RI refers to the random index depend on the value of n. The average RI derived from a sample size of 500 is generated by Saaty (1987). The value of CR should be less than 0.10 in order to ensure a certain level of consistency. If it is not satisfied, the previous judgement regarding to the relative importance of the criteria has to be revised (Saaty, 1987).

VI. **Evaluation of the goal**: Evaluate the achievement of the objective (i.e., degree of sustainability) by using the priorities scale obtained in previous step. The process alternatives are ranked according to its degree of sustainability. Figure 7.4 shows the summary of the aforementioned steps

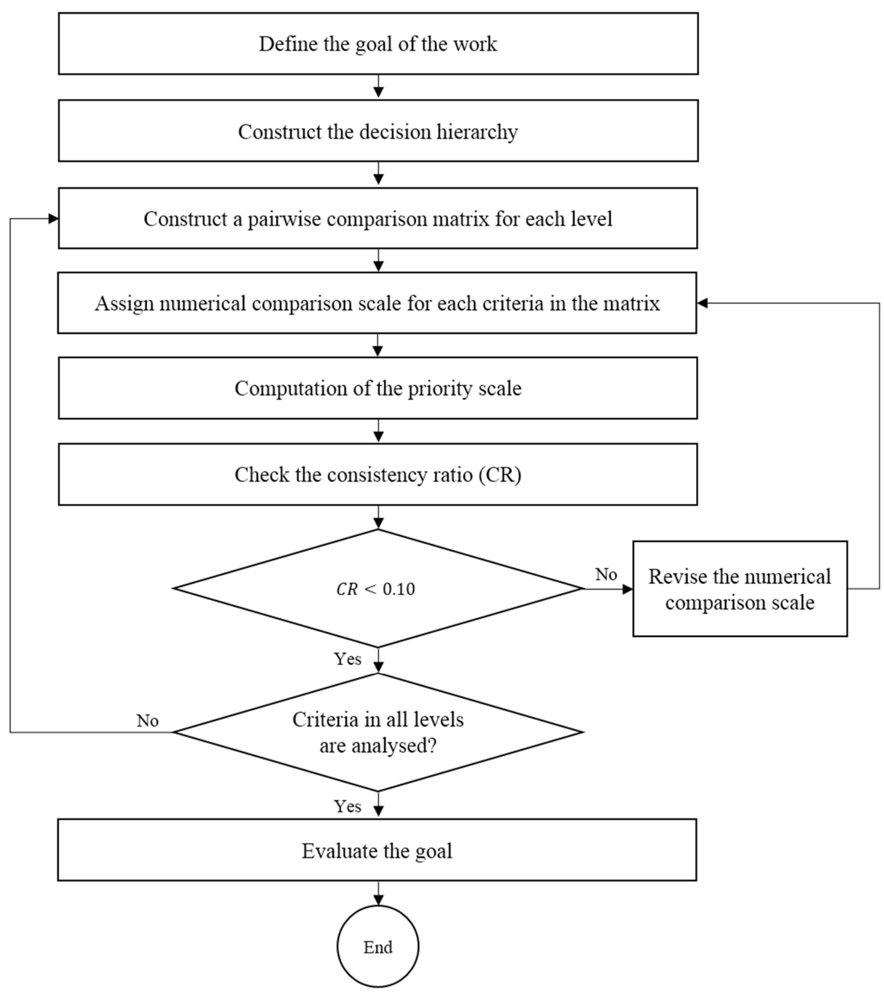

Figure 7.4: Analytical hierarchy process.

7.4.4 Multi-objective optimisation approach

In this section, a novel optimisation approach based on PCA method is proposed. Aside from this, the obtained optimised results are compared with the two conventional optimisation approaches, namely weighted sum approach and max-min aggregation approach. The optimisation formulation is given in the sub-sections below:

7.4.4.1 Weighted sum approach

Weighted sum approach is one of the simplest optimisation method. It allows to transform a set of objectives into a single objective by assigning a preferred priority scales to each objective. This approach has been introduced in Chapter 6, while the objective function is now revised to incorporate social impacts into the model:

$$max\ \lambda^{\mathrm{SCM}} = \mathrm{w}^{\mathrm{Ec}} \times \lambda^{\mathrm{Ec}} + \mathrm{w}^{\mathrm{En}} \times \lambda^{\mathrm{En}} + \mathrm{w}^{\mathrm{Sc}} \times \lambda^{\mathrm{Sc}} \tag{7.21}$$

$$\mathrm{w}^{\mathrm{Ec}} + \mathrm{w}^{\mathrm{En}} + \mathrm{w}^{\mathrm{Sc}} = 1 \tag{7.22}$$

where λ^{Sc} refers to the degree of satisfaction based on the social sustainability, while w^{Sc} refers to the priority scale assigned to the social sustainability based on the AHP result. Equation (7.22) assure that the summation of these weightage is equal to 1.

Note that λ^{Ec} and λ^{En} can be determined by using the formulation listed in Chapter 6 (refer to Equations (6.18) and (6.19)), while λ^{Sc} is calculated by using equation below:

$$\lambda^{\mathrm{Sc}} = \sum_u \lambda_u^{\mathrm{Sc}} \times \mathrm{w}_u \tag{7.23}$$

$$\lambda_u^{\mathrm{Sc}} = \begin{cases} \left.\frac{SI_u^{(\mathrm{U})}-SI_u}{SI_u^{(\mathrm{U})}-SI_u^{(\mathrm{L})}}\right|_{u\neq JC} \\ \left.\frac{SI_u-SI_u^{(\mathrm{L})}}{SI_u^{(\mathrm{U})}-SI_u^{(\mathrm{L})}}\right|_{u=JC} \end{cases} \qquad \forall u \in U \qquad (7.24)$$

where $\mathrm{SI}_u^{(\mathrm{U})}$ [t-eq/y] and $\mathrm{SI}_u^{(\mathrm{L})}$ [t-eq/y] refer to the upper and lower limit of the social impact at category *u* caused by the entire supply chain respectively (obtained by maximising and minimising Equation (7.1)), λ_u^{Sc} refers to the degree of satisfaction of each social impact *u*, while w_u refers to the relative importance of each social impact. Note that the minimisation case is used for social impacts such as HTPE, HTPI, ISI and risk of pedestrian fatality; while the maximisation case is used for job creation.

7.4.4.2 Max-min aggregation approach

Max-min aggregation approach is one of the most widely utilised fuzzy optimisation method nowadays. This approach ensures that the objectives in the model will not be over-improved while omitting the importance of the other objectives (Ng et al., 2016). By using this approach, the degree of satisfaction for the least satisfied objective, λ^{Least} is being maximised:

$$max\ \lambda^{\mathrm{Least}} \qquad (7.25)$$

$$\lambda^{\mathrm{Least}} \leq \lambda^{\mathrm{Ec}} \qquad (7.26)$$

$$\lambda^{\mathrm{Least}} \leq \lambda^{\mathrm{En}} \qquad (7.27)$$

$$\lambda^{\mathrm{Least}} \leq \lambda^{\mathrm{Sc}} \qquad (7.28)$$

7.4.4.3 PCA-aided approach

PCA allows to transform a larger series of original variables into a smaller series of PCs. The PCs of a data set are determined by solving an eigenvalue-eigenvector problem for the covariance matrix of the data set. However, the properties of PCA have some undesirable features when dealing with variables under different units of measurement (Jolliffe & Cadima, 2016). Thus, in order to address this issue, correlation matrix, $\boldsymbol{C}$ which involves standardisation of dataset is used instead of covariance matrix (Al-Sayed, 2015). The correlation between variables is defined as Equation (7.29), where *n* refers to the number of possible solutions; x_α and $x_\beta$are the variables; $\bar{x}_\alpha$ and $\bar{x}_\beta$ are the mean value of these variables; while σ_{x_α} and σ_{x_β} are the standard deviation of these variables.

$$corr(x_\alpha, x_\beta) = \frac{1}{n-1}\sum_1^n \left(\frac{x_\alpha - \bar{x}_\alpha}{\sigma_{x_\alpha}}\right)\left(\frac{x_\beta - \bar{x}_\beta}{\sigma_{x_\beta}}\right) \tag{7.29}$$

Therefore, in our case, eigenvector, $\boldsymbol{E}$ can be computed by using Equation (7.30) (assume det($\boldsymbol{C} - \lambda^{\mathrm{PC}} \cdot \boldsymbol{I}$) = 0, where $\boldsymbol{I}$ refers to the identity matrix). Note that the first PC (PC1) is corresponded to the largest eigenvalue λ^{PC}, indicates that PC1 explains the largest portion of the problem's variance, followed by second PC (PC2), and so on.

$$\boldsymbol{C}\,\boldsymbol{E} = \lambda^{\mathrm{PC}} \cdot \boldsymbol{E} \tag{7.30}$$

Finally, the sustainability performance of the solutions can now be redefined and represented in the PC space by using the PCs scores (also named as factor scores) (Abdi & Williams, 2010). It is defined in Equation (7.31), where $\boldsymbol{S}$ refers to the standardised original data matrix:

$$PC\ Score = \boldsymbol{S}\ \boldsymbol{E} \tag{7.31}$$

Note that the standardised value of data, $x^{\text{standardised}}$ (used in the matrix $\boldsymbol{S}$) is determined via Equation (7.32), where $\bar{x}$ refers to the mean of the original data series; while σ_x refers to the standard deviation of the original data series:

$$x^{\text{standardised}} = \frac{x-\bar{x}}{\sigma_x} \tag{7.32}$$

In this work, a threshold cut (TC) of 90 % is set to ensure the considered PCs are sufficient to describe the problem, while keeping the loss of information at minimal:

$$\text{TC} \leq \sum_z VAR_z \tag{7.33}$$

where VAR_z refer to the total variance described by first z of PCs. As already mentioned, PCs consist of a convex combination of original variables, while each variable has different optimisation direction (maximise or minimise). Therefore, it is vital to identify the correlation between these variables and PCs (directly-correlated or inversely-correlated) and their contribution rate. Note that the correlation can be determined by using Equation (7.34), while contribution is calculated through Equation (7.35), where $\boldsymbol{Y}$ refers to the projection matrix which shows correlation between the original variables and the PCs; while $e_{b,z}$ denotes the eigenvector assigned to variable b on the z^{th} PC:

$$\boldsymbol{Y} = \sqrt{\lambda^{\text{PC}}} \cdot \boldsymbol{E} \tag{7.34}$$

$$Contribution_{b,z} = \frac{(e_{b,z})^2}{\sum_b (e_{b,z})^2} \times 100 \quad \forall b \in B, \forall z \in Z \tag{7.35}$$

Table 7.3 is used to demonstrate how the PCs can be optimised, where "+" and "-" sign in 2nd column indicates that the variable is increased or decreased with PCs (identified through Equation (7.34)), "+" and "-" sign in 3rd column that the variable has to be maximised or minimised, 4th column refers to the contribution of each variable on PCs based on the described variance (determined using Equation (7.34), while 5th column refers to the priority scale set for each variable (obtained from AHP). The score is used to determine optimisation direction for PCs, where "+" sign is used when 2nd and 3rd columns have the same sign (e.g., V1 and V2), while "-" sign is used when 2nd and 3rd columns have different sign (e.g., V3). Note that "+" sign for the net direction indicates that the corresponding PC has to be maximized while "-" sign indicates minimisation case.

Table 7.3: Concept for PCA-aided optimisation approach.

Variables	Correlation	Direction	Contribution (%)	Priority scale (%)	Score
V1	+	+	10	40	+0.1*0.4
V2	-	-	50	40	+0.5*0.4
V3	+	-	40	20	-0.4*0.2
Net direction=					+0.16

The objective function of this optimisation approach is defined as in Equation (7.36), where λ^{PC_z} refers to the degree of satisfaction of z^{th} PC (or PC_z), while VAR_z [%] denotes%] denotes the total variance described by z^{th} PC.

$$\max \sum_z (\lambda^{PC_z} \times VAR_z) \tag{7.36}$$

λ^{PC_z} is defined based on fuzzy concept, where $PC_z^{(\mathrm{U})}$ and $PC_z^{(\mathrm{L})}$ refer to the maximal and minimal score for the z^{th} PC:

$$\lambda^{\mathrm{PC}_z} = \begin{cases} \left.\frac{PC_z^{(\mathrm{U})} - PC_z}{PC_z^{(\mathrm{U})} - PC_z^{(\mathrm{L})}}\right|_{Net\ direction<0} \\ \left.\frac{PC_z - PC_z^{(L)}}{PC_z^{(\mathrm{U})} - PC_z^{(\mathrm{L})}}\right|_{Net\ direction>0} \end{cases} \quad \forall z \in Z \tag{7.37}$$

7.5 Case Study Description

The same case study in Johor state is extended to cover the social impacts in the supply chain. The entire case study is decomposed into two stages: (i) technology selection, which aims to determine the optimal biomass conversion pathway for each biomass; and (ii) transportation design which aims to determine the optimal location to set up processing hub and the optimal biomass allocation design for the biomass industry. The extended information is listed below:

7.5.1 Social assessment

The sources of each environmental impact (i.e., GWP, ODP, POCP, AP, NP, ADP, ATP, TTP, WF and LF) are discussed in this subsection:

7.5.1.1 HTPE and HTPI

The HTPE and HTPI score for each material is tabulated in Table 7.4.

7.5.1.2 ISI

The ISI score for each technology is determined according to the user manual proposed by Hurme and Heikkilä (1998). These scores are tabulated in Table 7.5.

Table 7.4: Human toxicity potential score (Score obtained from WAR algorithm software (WAR GUI, 2011)).

Material	HTPE [m^3/mg]	HTPI [kg/mg]	Material	HTPE [m^3/mg]	HTPI [kg/mg]
CO_2	0.0001	0.0000	Bio-char	0.000	0.1687
CH_4	0.0015	0.0000	Energy Pack	0.2000	0.0020
CO	0.0182	0.0000	Bio-ethanol	0.0001	0.0001
N_2O	0.0111	0.0000	Citric acid	0.0000	0.0001
SO_2	0.0769	0.0000	Syngas	0.0048	0.0000
Py-oil	0.2000	0.0020	DLF	0.0000	0.0000

Table 7.5: Inherent safety index (ISI) (Score is assigned based on guideline given by Heikkilä (1999).

SCM Activities	ISI	SCM Activities	ISI
DLF production	12	Citric Acid Production	25
Energy Pack production	13	Anaerobic digestion	30
Gasification	34	Animal feed production	9
Fast pyrolysis	31	Fertiliser production	15
Slow pyrolysis	30	Combustion	35
Bio-ethanol Production	22[a]		
	22[b]		
	24[c]		
	26[d]		

[a] Undergo dilute acid pre-treatment.
[b] Undergo dilute alkaline pre-treatment.
[c] Undergo hot water pre-treatment.
[d] Undergo steam explosion pre-treatment.

7.5.1.3 Transportation safety

Numerous studies have found the relationship between the vehicle size to the risk of fatality during an accident (NHTSA, 1997). It is expected that larger vehicle will lead to higher risk of pedestrian fatality since larger vehicle carries greater kinetic energy compared to the smaller vehicle at the same speed. By assuming the linear correlation between risk of pedestrian fatality and the kinetic energy carried by the vehicle (see Equation 7.38), Figure 7.5 which shows the estimated risk of pedestrian fatality for each transportation mode is constructed.

$$P_m^{\text{Fatality}} \propto 0.5\ Weight_m\ \text{Sp}_m^{\text{Impact}^2} \qquad \forall m \in M \tag{7.38}$$

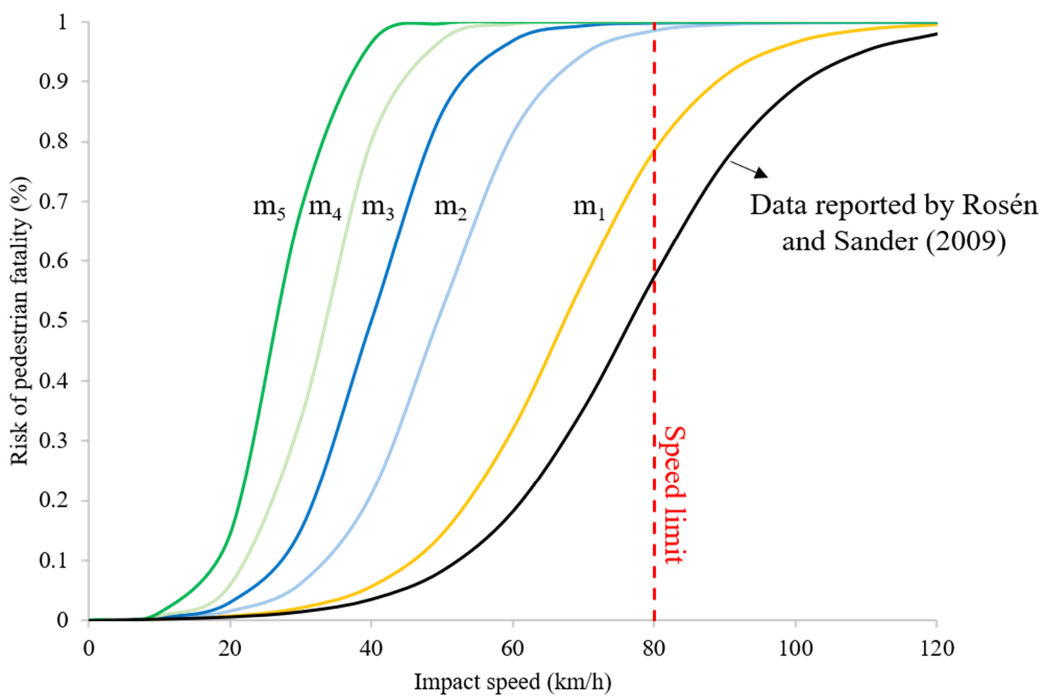

Figure 7.5: Risk of pedestrian fatality.

To illustrate, a vehicle which moving at 70 km/h will carry 0.53 kJ of energy. According to Equation (7.14) (vehicle mass, $Weight_m$ reported in Rosén and Sander (2009) is assumed at 2.8 t), the calculated P_m^{Fatality} is 0.3543. However, based on the assumption made in Equation (7.38), same kinetic energy is carried by other transportation modes when they are moving at driving speed (i.e., m_1: 61 km/h; m_2: 45km/h; m_3: 36 km/h; m_4: 30 km/h; m_5: 24 km/h). Thus, it is assumed that the P_m^{Fatality} for these vehicle modes under the corresponding speed is equal to 0.3543 (similar to the P_m^{Fatality} reported by Rosén and Sander (2009) when driving speed is set at70 km/h). Note that the mass of each vehicle modes is tabulated in Table 7.6.

Table 7.6: Mass of each vehicle modes

Transportation mode	$Weight_m$ [t]
m_1	3.6
m_2	6.7
m_3	10.3
m_4	14.9
m_5	22.7
Reported in Rosén and Sander (2009)	2.8

7.5.1.4 Job creation

Aside from the significant economic increment and substantial environmental benefit, the commercialisation will also create considerable amount of incremental jobs (MIGHT, 2013). Table 7.7 tabulates the estimated job creation for each process.

Table 7.7: Job creation.

SCM Activities	Job creation	Reference
DLF production	0.002 [job/t fibre]	(FAO, 2014)
Energy Pack production[a]	0.0215 [job/t EP]	-
Gasification/Pyrolysis	0.004 [job/ m^3 bio-oil]	(Maia et al., 2011)
Bio-ethanol Production	0.01 [job/m^3 bio-ethanol]	(Sustek, 2011)
Citric Acid Production[b]	0.005 [job/m^3 citric acid]	-
Anaerobic digestion	2.21 [job/MW]	(McDermott, 2012)
Animal feed/fertiliser production	0.0004 [job/t product]	(Chen, 2016)
Combustion	0.5759 [job/MW]	(Maia et al., 2011)

[a] Value estimated based on energy generated (compared with combustion technology)
[b] Value estimated based on the job creation of succinic acid (Gatto, 2013)

7.5.2 Analytical Hierarchy Process (AHP)

The sustainable dimensions were evaluated using AHP, where the numerical comparison scale was identified through expert judgement. The data is collected through questionnaire survey (15 respondents). Please refer to Appendix Section A.4.1 for the questionnaire sample). In order to aggregate all these individual judgements into a single comparison matrix, geometric mean method is opted (Dong et al., 2010). The geometric mean is defined as in Equation (7.39):

$$\left(\prod_{s=1}^{s} Score_s\right)^{\frac{1}{s}} = \sqrt[s]{Score_1 \times Score_2 \times \ldots\ Score_3} \qquad (7.39)$$

where $Score_s$ refers to the priority score assigned by each responder *s*, while *s* refers to the number of responders. To illustrate, assumed there are three respondents (A, B and C), where the relative individual judgement is tabulated in Table 7.8. Then, geometric mean of each numerical comparison scale is determined and the pairwise comparison matrix constructed as Table 7.9. The pairwise comparison matrix and the determined relative priority scale of each objective is tabulated in Table 7.10.

Table 7.8: Sample individual judgement.

	EC	EN	SC	Respondent
EC	1	2	5	A
EN	1/2	1	3	
SC	1/5	1	1/3	
EC	1	2	2	B
EN	1/2	1	1	
SC	1/2	1	1	
EC	1	1/2	2	C
EN	2	1	3	
SC	1/2	1/3	1	

*EC=Economic; EN=Environmental; SC=Social

Table 7.9: Pairwise comparison matrix example.

	EC	EN	SC
EC	1	$\sqrt[3]{2 \cdot 2 \cdot 1/2} = 1.26$	$\sqrt[3]{5 \cdot 2 \cdot 2} = 2.71$
EN	$\sqrt[3]{1/2 \cdot 1/2 \cdot 2} = 0.79$	1	$\sqrt[3]{3 \cdot 1 \cdot 3} = 2.08$
SC	$\sqrt[3]{1/5 \cdot 1/2 \cdot 1/2} = 0.37$	$\sqrt[3]{1/3 \cdot 1 \cdot 1/3} = 0.48$	1

*EC=Economic; EN=Environmental; SC=Social

Table 7.10: Pairwise comparison for the sustainability dimensions.

	EC	**EN**	**SC**	**Relative weight, *w***	**Rank**
EC	1	2	2	0.50	1
EN	1/2	1	1	0.25	2
SC	1/2	1	1	0.25	2
CR	0			Total = 1	-

*EC=Economic; EN=Environmental; SC=Social

7.6 Result and Discussion

The results and discussions are given in the following subsections:

7.6.1 PCA-aided optimisation approach

As already mentioned, the entire case study is decomposed into two parts: (i) technology selection and (ii) transportation design:

7.6.1.1 Technology selection

This stage aims to determine the optimal biomass conversion pathway for each biomass. In this case study, there are more than 500 possible solutions for the technology selection. The sustainability performances in terms of economic, environmental and social dimension of each solution are determined by using the formulated model. Then, these series of data are processed through PCA in order to reduce the data redundancy. Figure 7.6 shows that two PCs are sufficient to describe the data (since $\sum_{z=2} VAR_z > 90\ \%$). Therefore, each solution is now represented in terms of PC1 and PC2 (see Figure 7.7). These diagrams are constructed by using a closed access Excel add-in (XLSTAT, 2017). Note that the dark green dots are the possible solutions in this case study.

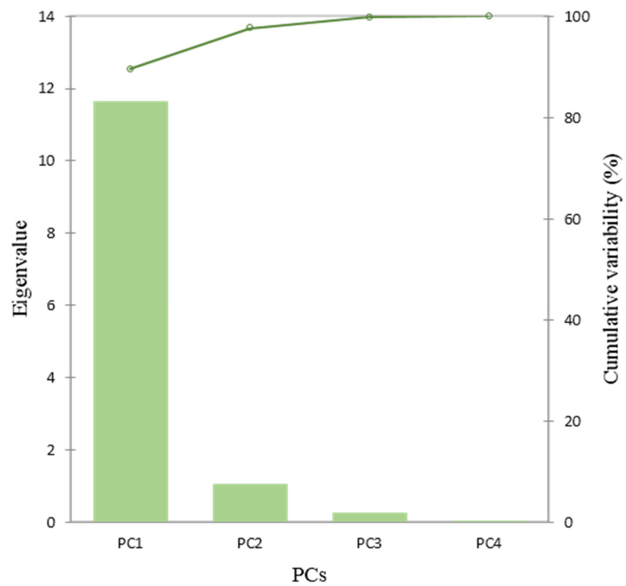

Figure 7.6: PCA for technology selection (XLSTAT, 2017).

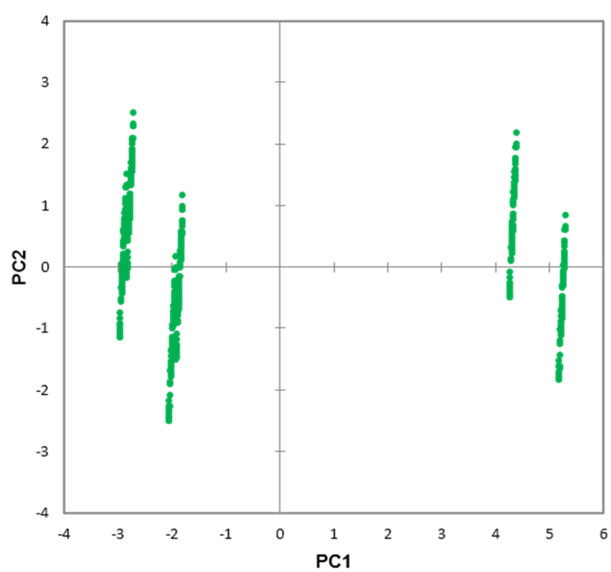

Figure 7.7: PC score for technology selection (XLSTAT, 2017).

Table 7.11 and Table 7.12 are constructed in order to determine the optimisation direction of PC1 and PC2.

Table 7.11: PCA-aided optimisation for technology selection (PC1).

Variables	Correlation	Direction	Contribution	Priority scale [%]	Score*
$\boldsymbol{C}^{\mathbf{GP}}$	+	+	7.984	50.00	7.984 x 0.5 = 3.992
GWP	-	-	7.986	25.00	7.986 x 0.25/8 = 0.250
AP	-	-	8.182		8.182 x 0.25/8 = 0.256
POCP	+	-	8.393		-8.393 x 0.25/8 = -0.262
NP	+	-	8.426		-8.426 x 0.25/8 = -0.263
ATP	+	-	8.453		-8.453 x 0.25/8 = -0.264
TTP	+	-	8.445		-8.445 x 0.25/8 = -0.264
ADP	-	-	8.174		8.174 x 0.25/8 = 0.255
WF	+	-	8.431		-8.431 x 0.25/8 = -0.263
HTPI	+	-	8.445	25.00	-8.445 x 0.25/4 = -0.528
HTPE	+	-	8.379		-8.379 x 0.25/4 = -0.524
ISI	+	-	0.268		-0.268 x 0.25/4 = -0.017
JC	+	+	8.435		8.435 x 0.25 = 0.527
Net direction =					+2.895

*Positive when the sign in 2nd and 3rd columns are the same; negative when the sign in 2nd and 3rd columns are diferent

Table 7.12: PCA-aided optimisation for technology selection (PC2).

Variables	Correlation	Direction	Contribution	Priority scale [%]	Score*
C^{GP}	-	+	0.534	50.00	-0.534 x 0.5 = -0.267
GWP	+	-	1.421	25.00	-1.421 x 0.25/8 = -0.044
AP	+	-	1.058		-1.058 x 0.25/8 = -0.033
POCP	-	-	0.968		0.968 x 0.25/8 = 0.030
NP	+	-	0.451		-0.451 x 0.25/8 = -0.014
ATP	+	-	0.464		-0.464 x 0.25/8 = -0.014
TTP	+	-	0.497		-0.497 x 0.25/8 = -0.016
ADP	+	-	0.940		-0.940 x 0.25/8 = -0.029
WF	+	-	0.553		-0.553 x 0.25/8 = -0.017
HTPI	+	-	0.497	25.00	-0.497 x 0.25/4 = -0.031
HTPE	-	-	1.259		1.259 x 0.25/4 = 0.079
ISI	+	-	90.826		-90.83 x 0.25/4 = -5.677
JC	+	+	0.534		0.534 x 0.25/4 = 0.033
Net direction =					-6.000

*Positive when the sign in 2nd and 3rd columns are the same; negative when the sign in 2nd and 3rd columns are diferent

The results show that PC1 should be maximised while PC2 should be minimised. Note that the priority scales used for each objective are determined through AHP, while assuming all the sub-indexes for environmental and social dimension are equally important (e.g., GWP is equally important to other environmental impacts; HTPI is equally important to other social impacts). Similar optimal results are obtained compared to the solution obtained from previous chapter (see Section 4.5.1, Figure

4.14), but the selected pre-treatment for the sugarcane bagasse in the bio-ethanol production has shifted from hot-water pre-treatment to dilute alkaline pre-treatment, while pineapple peels are used as the feedstock for animal feed production (see Figure 7.8). This is probably due to the lower social impacts for the current selected technologies (lower ISI for these technologies compared to others).

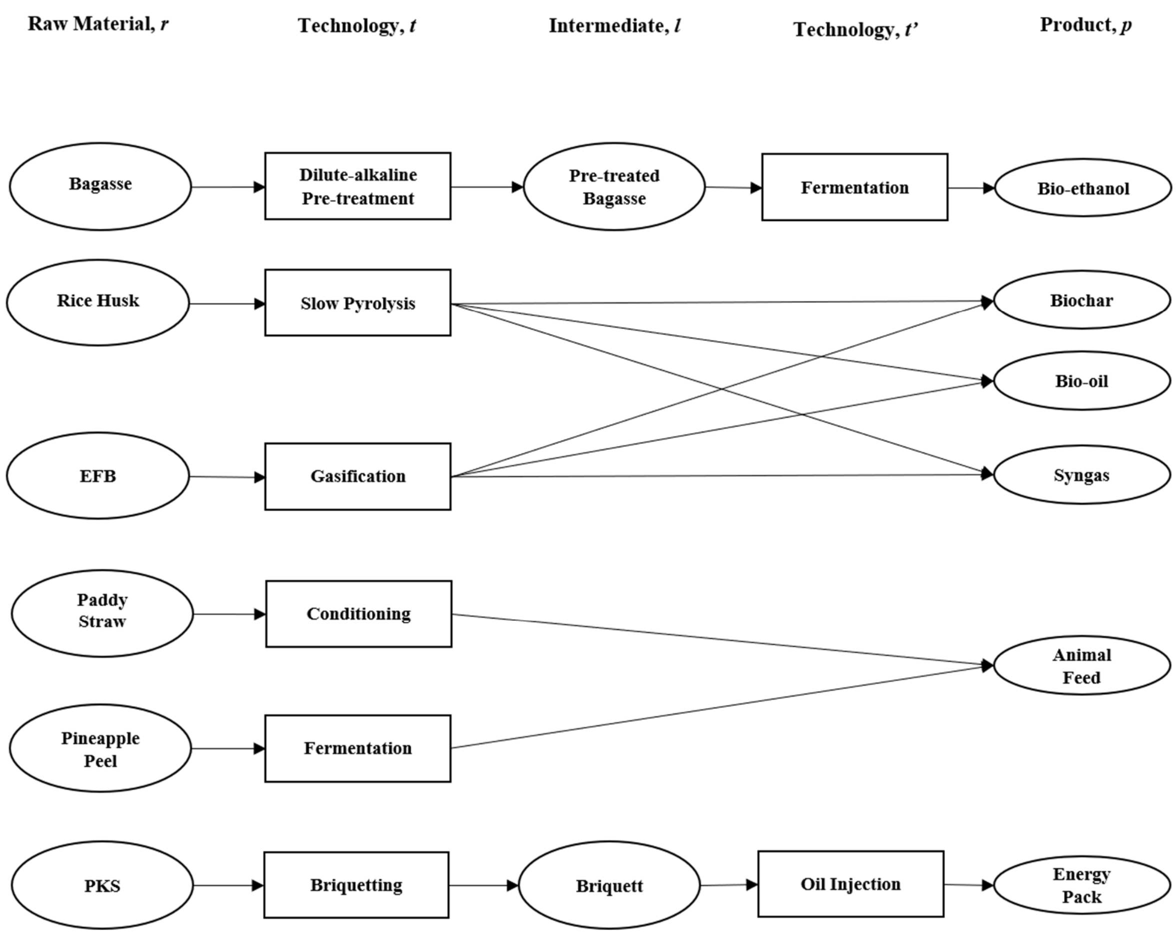

Figure 7.8: Optimal technology selection via PCA-aided approach.

7.6.1.2 Transportation design

This stage aims to determine the optimal location to set up processing hub and the optimal biomass allocation design for the biomass industry. In this case study, the average driving speed, $\mathrm{Sp}_m^{\mathrm{Mean}}$ during transportation is assumed to be either 50 km/h, 60 km/h or 70 km/h. Similarly, the sustainability performances of each solution are determined by using the formulated evaluation model. The PCA results show that that three PCs are sufficient to describe more than 90 % of the total variance (see Figure 7.9). Therefore, as shown in Figure 7.10, each solution is now redefined in terms of PC1, PC2 and PC3. Note that the PC1 and PC2 mentioned in this section is different from the one mentioned in previous section.

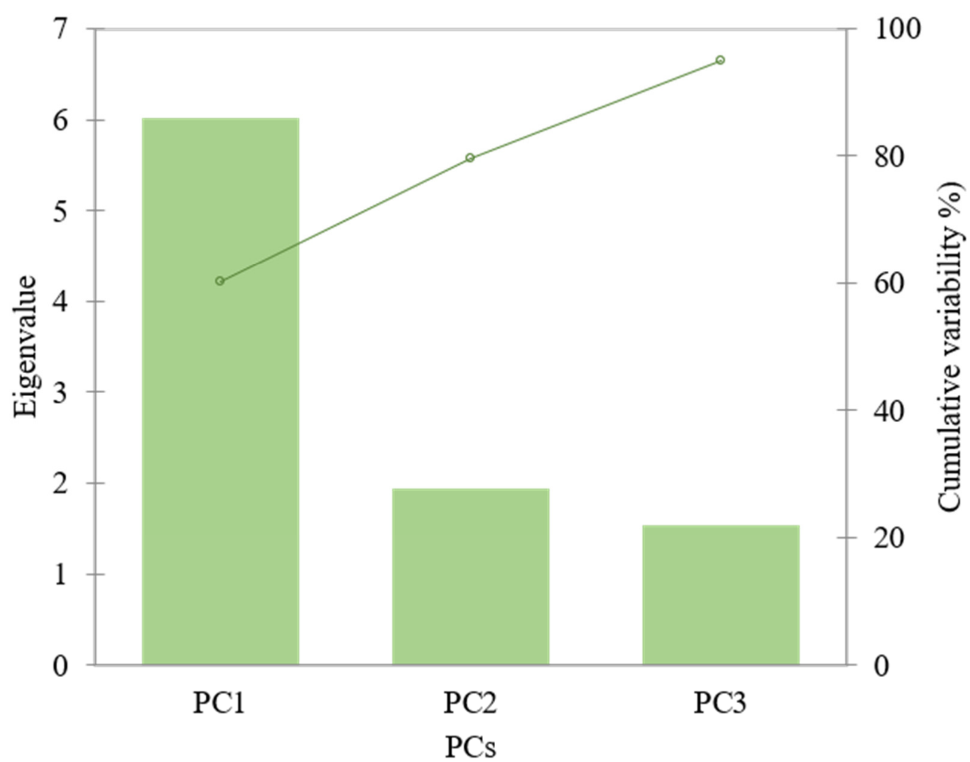

Figure 7.9: PCA for transportation design (XLSTAT, 2017).

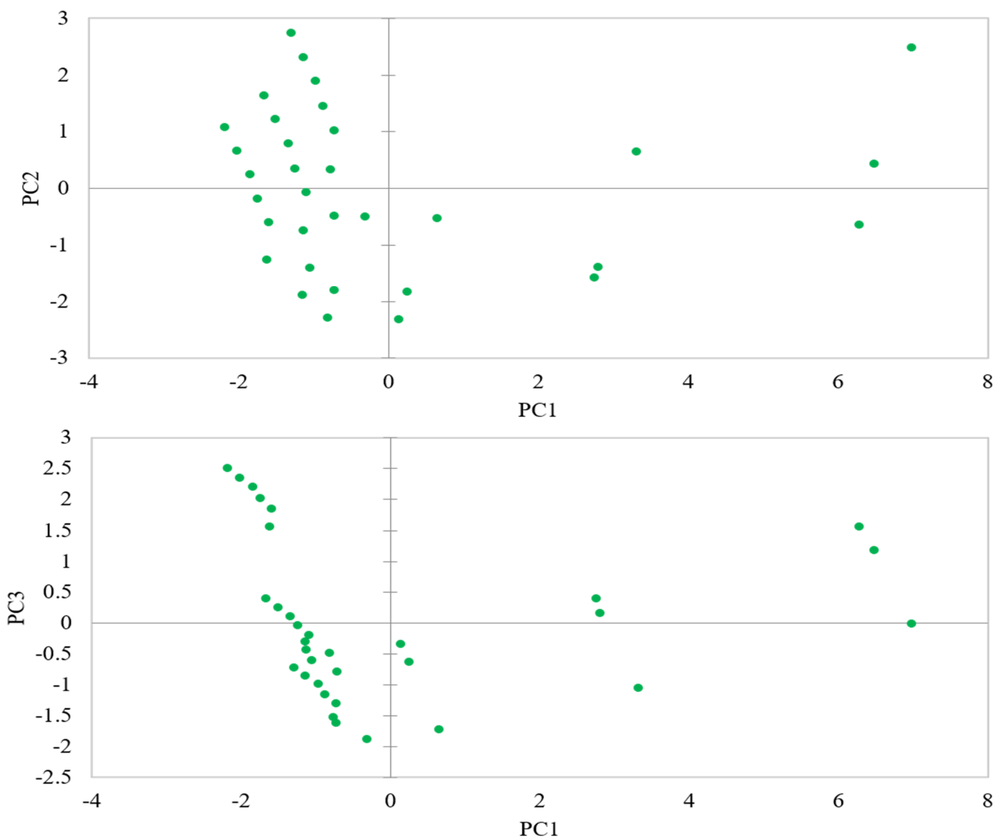

Figure 7.10: PC score for transportation design (XLSTAT, 2017).

Table 7.13, Table 7.14 and Table 7.15 are constructed in order to determine the optimisation direction of PC1, PC2 and PC3. Note that C^{Inv} [RM/y] refers to the investment cost required (i.e., summation of $C^{\mathrm{Inv\_Hub}}$ and C^{Tr}). The result shows that all three PCs have to be minimised (net score is less than zero). The model suggests to increase the number of hubs to four (the optimal number of hubs obtained in Chapter 6 is three). As mentioned in Chapter 5, more hubs will lead to lower transportation cost and lesser emissions, but higher hub investment cost as a trade-off. In addition, it also suggests to increase the average driving speed, $\mathrm{Sp}_m^{\mathrm{Mean}}$ to 70 km/h (instead of 60 km/h) in order to further improve the economic viability of the supply chain.

Table 7.13: PCA-aided optimisation for transportation design (PC1).

Variables	Correlation	Direction	Contribution	Priority scale [%]	Score*
C^{Inv}	-	-	4.283	50.00	4.283 x 0.5 = 2.141
GWP	+	-	15.798	25.00	-15.798x 0.25/7 = -0.564
AP	+	-	15.812		-15.798 x 0.25/7 = -0.564
POCP	-	-	2.070		2.070 x 0.25/7 = 0.074
NP	+	-	15.812		-15.812 x 0.25/7 = -0.564
ATP	+	-	1.510		-1.510 x 0.25/7 = -0.054
ADP	+	-	15.812		-15.812 x 0.25/7 = -0.564
LF	-	-	10.013		10.013 x 0.25/7 = 0.357
HTPE	+	-	15.812	25.00	-15.812 x 0.25/2 = -1.976
Risk	-	-	3.077		3.077 x 0.25/2 = 0.384
Net direction =					-1.331

*Positive when the sign in 2nd and 3rd columns are the same; negative when the sign in 2nd and 3rd columns are diferent

Table 7.14: PCA-aided optimisation for transportation design (PC2).

Variables	Correlation	Direction	Contribution	Priority scale [%]	Score*
C^{Inv}	+	-	32.318	50.00	-32.318 x 0.5 = -16.159
GWP	+	-	0.375	25.00	-0.375 x 0.25/7 = -0.013
AP	+	-	0.348		-0.348 x 0.25/7 = -0.012
POCP	+	-	0.000		-0 x 0.25/7 = 0
NP	+	-	0.348		-0.348 x 0.25/7 = -0.012
ATP	+	-	42.600		-42.6 x 0.25/7 = -1.521
ADP	+	-	0.346		-0.346 x 0.25/7 = -0.012

Table 7.14(cont'): PCA-aided optimisation for transportation design (PC2).

Variables	Correlation	Direction	Contribution	Priority scale [%]	Score*
LF	+	-	16.198	25.00	-16.198 x 0.25/7 = -0.578
HTPE	+	-	0.348	25.00	-0.348 x 0.25/2 = -0.043
Risk	-	-	7.120		7.120 x 0.25/2 = 0.890
Net direction =					-17.463

*Positive when the sign in 2nd and 3rd columns are the same; negative when the sign in 2nd and 3rd columns are diferent.

Table 7.15: PCA-aided optimisation for transportation design (PC3).

Variables	Correlation	Direction	Contribution	Priority scale [%]	Score*
C^{Inv}	+	-	4.793	50.00	-4.793 x 0.5 = -2.397
GWP	+	-	2.558	25.00	-2.558 x 0.25/7 = -0.091
AP	+	-	2.537		-2.537 x 0.25/7 = -0.090
POCP	+	-	40.900		-40.9 x 0.25/7 = -1.460
NP	+	-	2.537		-2.537 x 0.25/7 = -0.090
ATP	-	-	1.649		1.649 x 0.25/7 = 0.059
ADP	+	-	2.536		-2.536 x 0.25/7 = -0.090
LF	+	-	3.318		-3.318 x 0.25/7 = -0.118
HTPE	+	-	2.537	25.00	-2.537 x 0.25/2 = -0.317
Risk	+	-	36.635		-36.6 x 0.25/2 = -4.579
Net direction =					-9.177

*Positive when the sign in 2nd and 3rd columns are the same; negative when the sign in 2nd and 3rd columns are diferent.

7.6.2 Benchmarking with other approaches

The optimal results obtained from two conventional optimisation approaches (please refer Section 7.4.4.1 to Section 7.4.4.2 for the model formulation; and Appendix Section A.4 for the model coding) and the one proposed in this wok are tabulated in Table 7.16 (technology selection) and Table 7.17 (transportation design). Table 7.16 shows that PCA-aided approach is able to provide equivalent result for the technology selection when compared to the weighted sum approach, while max-min aggregation approach provides different solutions in order to maximise the least satisfied objective (i.e., the environmental performance in this case).

Table 7.16: Optimised results obtained from each approach (technology selection).

	Weighted sum*	**Max-min aggregation**	**PCA-aided***
Technology Selection			
EFB	Gasification	Gasification	Gasification
PKS	Energy Pack Prod.	Energy Pack Prod.	Energy Pack Prod.
Rice husk	Slow Pyrolysis	Fast Pyrolysis	Slow Pyrolysis
Paddy straw	Fertiliser Prod.	Combustion	Fertiliser Prod.
Pineapple peel	Animal Feed Prod.	Animal Feed Prod.	Animal Feed Prod.
Sugarcane bagasse	Bio-ethanol Prod. (Dilute Alkaline Pre-treatment)	Bio-ethanol Prod. (Steam Explosion Pre-treatment)	Bio-ethanol Prod. (Dilute Alkaline Pre-treatment)
Sustainability Performance			
λ^{Ec}	0.9998	0.9985	0.9998
λ^{En}	0.3749	0.3759	0.3749
λ^{Sc}	0.4469	0.3870	0.4469

*Priority scales obtained from AHP (w^{Ec}= 50 %, w^{En} = 25 % and w^{Sc}= 25 %), it is adjustable

Table 7.17: Optimised results obtained from each approach (transportation design).

	Weighted sum*	Max-min aggregation	PCA-aided*
Transportation Design			
$num^{\mathbf{Hub}}$	3	4	4
$\mathbf{Sp}_m^{\mathbf{Mean}}$[km/h]	50	50	70
Sustainability Performance			
$\lambda^{\mathbf{Ec}}$	0.9126	0.8497	0.9353
$\lambda^{\mathbf{En}}$	0.8373	0.8935	0.9426
$\lambda^{\mathbf{Sc}}$	0.8645	0.9119	0.6053

* Priority scales obtained from AHP (w^{Ec}= 50 %, w^{En} = 25 % and w^{Sc}= 25 %), it is adjustable

For transportation design, the obtained optimised results are different in all three optimisation approaches. Both weighted sum approach and max-min aggregation approach suggests to use lower $\mathrm{Sp}_m^{\mathrm{Mean}}$ (i.e., 50 km/h) in order to mitigate the total risk of pedestrian fatality. In contrast, PCA which ranks the importance of variables based on the variation in data pattern will treat the transportation safety as non-factor (total risk varied from a range between 632.5 to 677.0, which is relatively tighter compared to other variables). Therefore, the beauty of this PCA-aided optimisation approach is the prioritisation method which integrates the priority scale obtained from AHP (which solely depending on experience of decision-makers) and from PCA (which merely based on data variation).

As a result, PCA suggests to further enhance the economic and environmental performance by using higher $\mathrm{Sp}_m^{\mathrm{Mean}}$ (i.e., 70 km/h). It is also worth noting that the optimised result obtained from the proposed approach is equivalent to the optimised result obtained from weighted sum approach (e.g., when priority scale: w^{Ec} = 40 %, w^{En} = 45 % and w^{Sc}= 10 %). Therefore, for this proposed case study, it can be concluded that PCA-aided optimisation approach is able to provide reliable and acceptable results compared to other optimisation approaches.

Aside from this, high traceability of the results is the practical advantage of the approach. For instance, in the proposed case study, PC2 used for technology selection is extensively contributed by inherent safety of processing hub. Hence, higher PC2 value indicates the solution will lead to higher ISI score (i.e., lower social sustainability). Therefore, instead of comparing the huge complex sets of original variables, decision-makers can now identify the potential bottleneck of the solution merely based on these PC scores.

7.6.3 Pareto analysis

In this section, Pareto analysis is conducted to investigate the effect of the priority scales assigned to the sustainability dimensions on the optimised result. The model formulated in Section 7.4 is used to determine the sustainability performance of each feasible solutions (e.g., different configuration of technologies). Then it is plotted in Figure 7.11 to show the relationship between performances of social and economic dimensions (Pareto analysis of ISI follows Pattern A; HTPI and HTPE follow Pattern B; JC follows Pattern C; while transportation risk follows Pattern D).

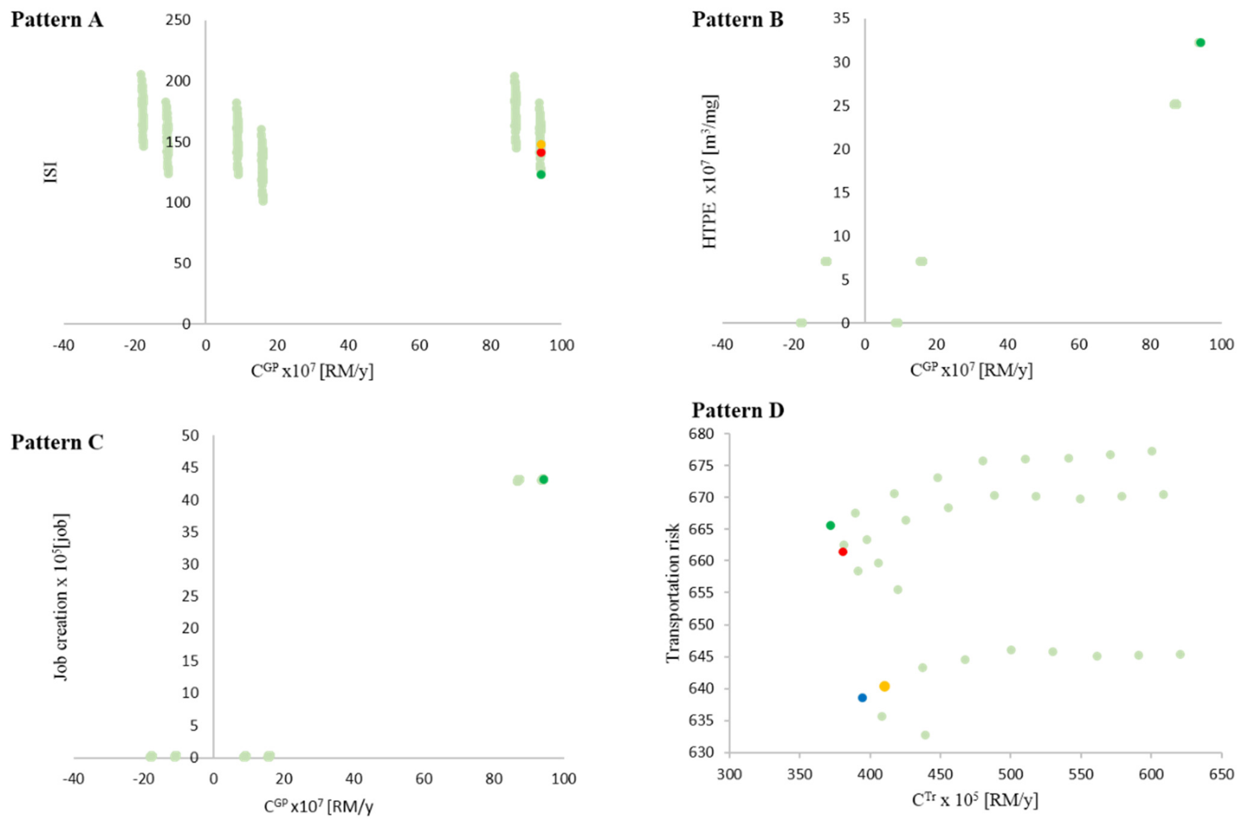

Figure 7.11: Pareto studies.

Again, this indicates that the relative importance (weightage) of each social impact is a critical factor that will affect the obtained optimal solution (in this work, they are assumed equally important). Note that the dark green dots represent the optimal solution obtained using PCA approach, red dots refer to the optimal solution obtained from Chapter 6, blue dots refer to the optimal solution obtained from weighted sum approach (w^{Ec}= 50 %, w^{En} = w^{Sc}= 25 %), while yellow dots refer to the optimal solution obtained from max-min aggregation approach. As already mentioned in Chapter 6, for weighted sum optimisation approach, the optimised results are sensitive and reliant on the priority scales assigned to each sustainability dimension. The results are summarised in Figure 7.12.

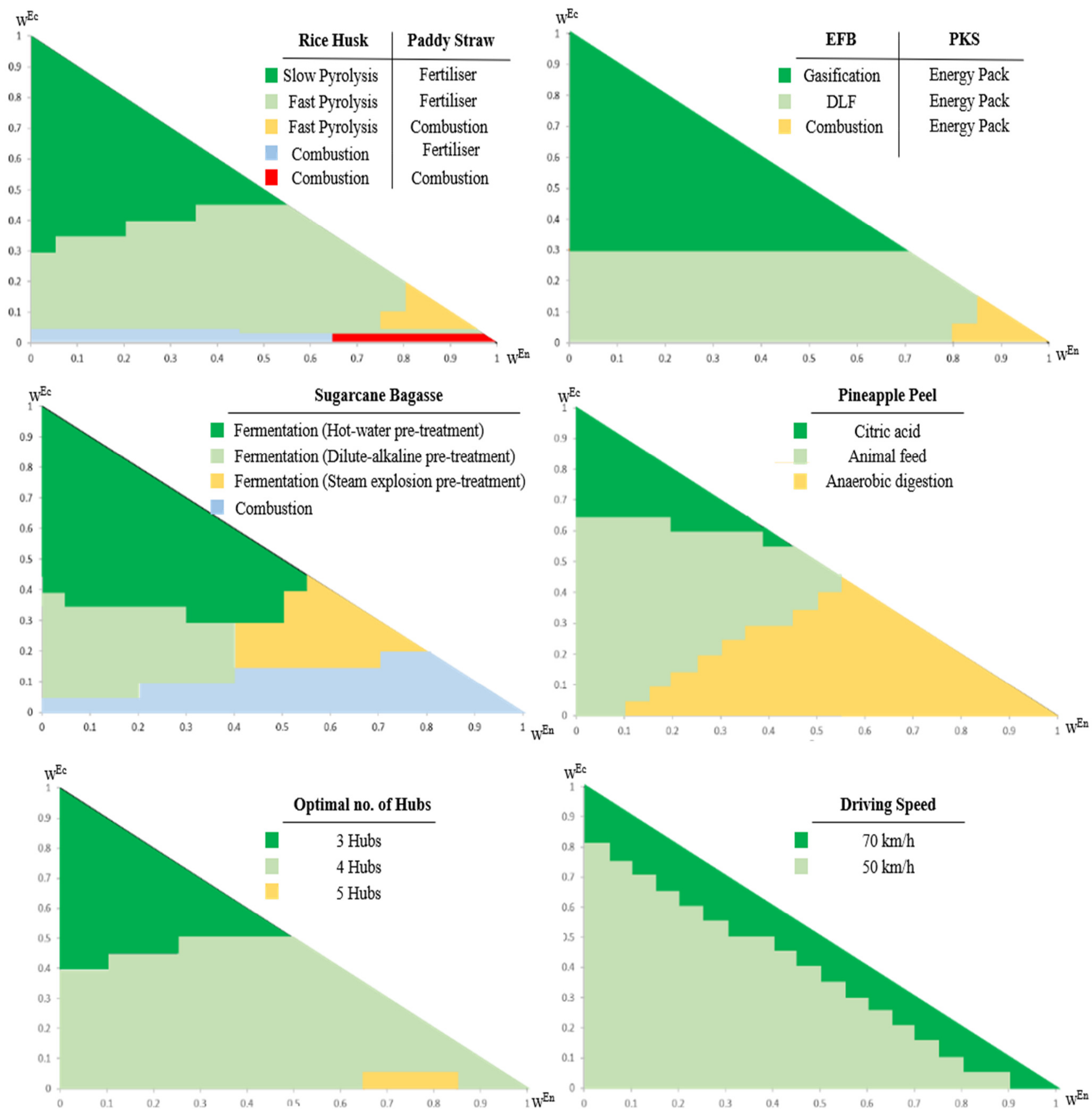

Figure 7.12: Effect of priority scales on weighted sum approach.

To illustrate, by reducing the priority scale for economic performance from 67 % to 20 %, while maintaining the priority scale for environmental performance at 33 %, EFB is no longer used as gasification feedstock but it is used for the DLF production. As a result, the overall profit has become 80 % lower (equivalent to RM 781,159,227/y), while, the overall HTPE and HTPI scores are reduced significantly (i.e., HTPE: 77.9 % lesser; HTPI: 99.2 % lesser). Similar to the model developed in Chapter 6, by setting a low priority scale for economic dimension, four processing hubs are optimal. Despite the higher risk of pedestrian fatality, the model will recommend the use of higher driving speed when a low priority scale for social dimension is set. These results indicate that the optimal solutions obtained from weighted sum approach are very reliant on the priority scales assigned to each objective.

7.6.4 Limitation

Since PCA method rank the input variables based on the data variation, the optimised results obtained from the proposed PCA-aided optimisation approach are also highly dependent on the data variation. In order to investigate the feasible data variation range for the obtained optimised results, Failure Analysis (or so-called Feasible Operating Range Analysis (FORA)) which introduced by Andiappan et al. (2017) is opted and modified. The generic concept and procedure for the Failure Analysis used in this work is stated below:

I. Let A, B, C be the input variables (or indicators) of the optimal solution. Note that this solution is obtained through PCA-aided optimisation approach.

II. The value of A is varied, while keeping B and C constant to determine the maximum and minimum allowable input value for A to obtain the same optimal solution. In other words, if the input A is lower than this minimum value (or higher than this maximum value), different optimal solution is obtained from the proposed PCA-aided optimisation approach.

III. Step II is then repeated for different input values of B. Normally, maximum and minimum values of B will be used. These values can be obtained by repeating step II while this time, keeping A and C constant and varrying B. The corresponding maximum and minimum allowable input values of A are noted respectively. The superimposed region for value A is then identified as shown by the shaded region in Figure 7.13.

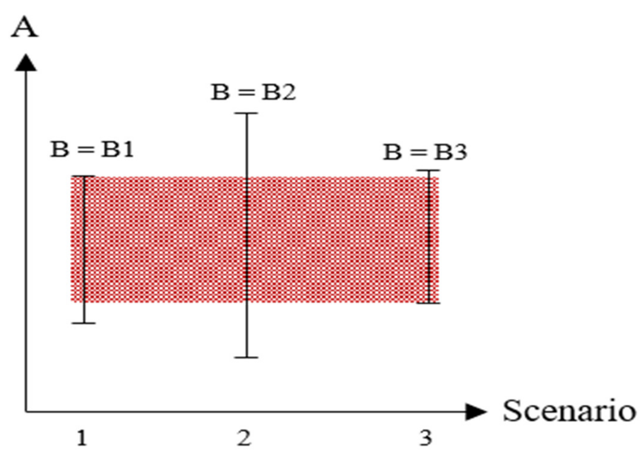

Figure 7.13: Failure Analysis (step III).

IV. Steps II and III are then repeated for several input values of C (similarly, maximum and minimum C is used). The superimposed region of A obtained from Step II and III are then determined (see Figure 7.14. This overlapping region of A values is noted as the feasible range of A which the same optimal solution is obtained from the proposed optimisation approach.

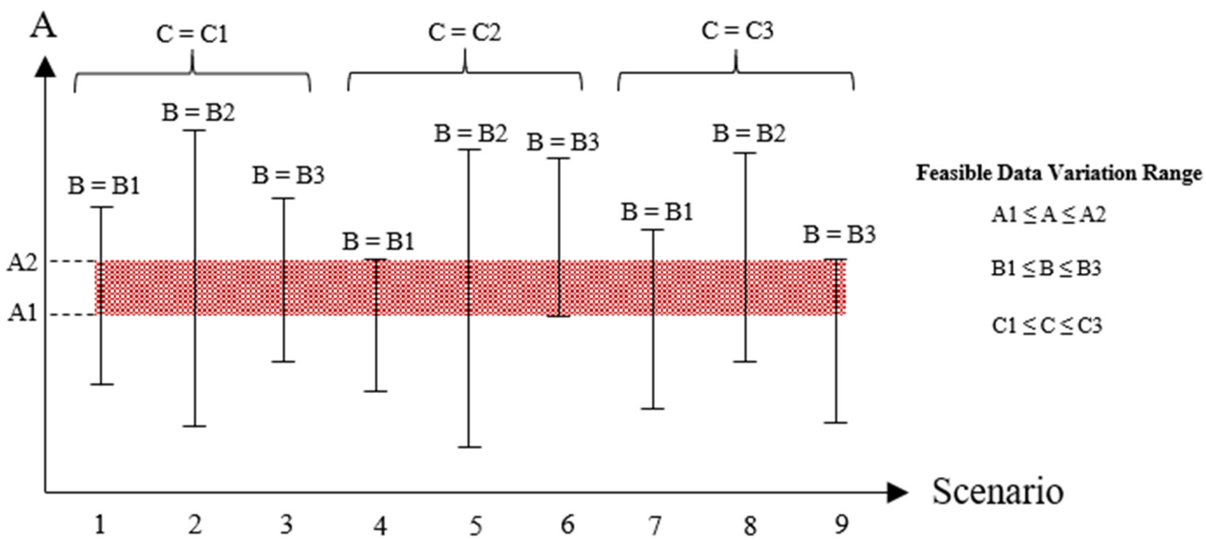

Figure 7.14: Failure Analysis (step IV).

V. Note that the number of input variables is not limited to three. Former steps (Step II to IV) are repeated if more variables are considered.

In this work, failure analysis is applied to determine the feasible data variation range of the obtained optimal solution for both technology selection and transportation design. Figure 7.15 shows the feasible data variation range of the optimal solution for technology selection (listed in Table 7.16). If the input data (i.e., economic performance, pollutant emission, safety concern and job creation) for this solution falls apart from the given ranges, different optimal solution will be obtained.

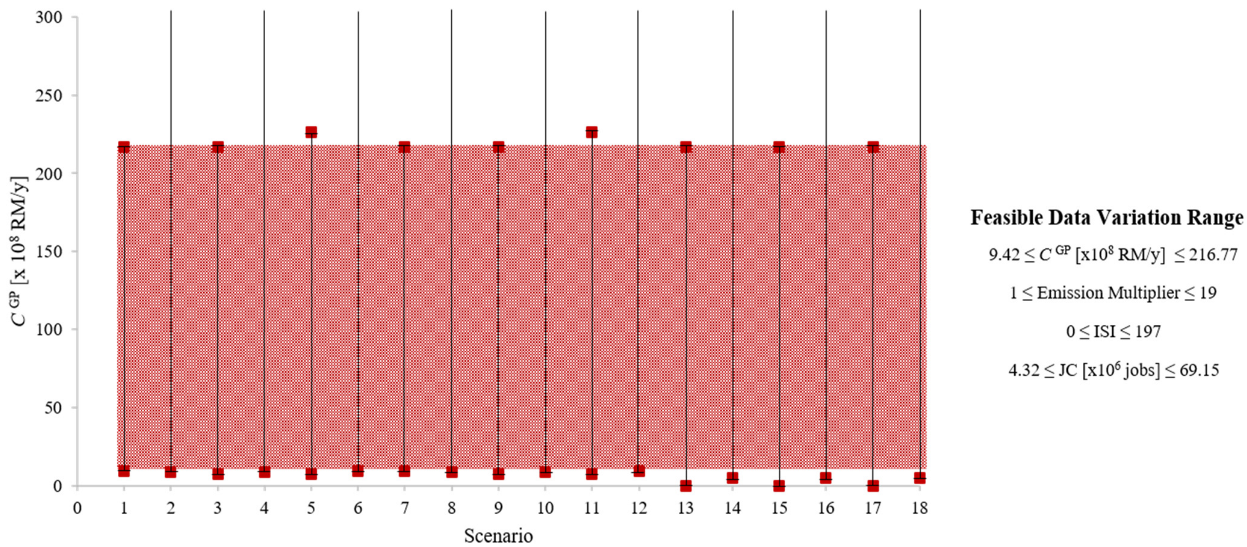

Figure 7.15: Failure Analysis (technology selection).

Instead of identifying the feasible range of each emission indicators (i.e., GWP, AP, POCP, ATP, NP, TTP, ADP, WF, HTPI and HTPE), the feasible range of the emission multiplier (i.e., emission factor used in this work) is identified. Note that, emission multiplier greater than 1 indicates higher emission rate compared to the current used emission rate; emission multiplier less than 1 indicates lower emission rate compared to the current emission rate; emission rate equal to 1 indicates the current used emission rate. The maximum and minimum value of this multiplier is obtained on the procedures mentioned above. It is then used to calculate the corresponding maximum and minimum value of each emission indicator (see Table 7.18). Table 7.19 shows the description for each scenario. To illustrate, scenario 8 is used to determine the feasible range for C^{GP} while assuming emission multiplier at maximum possible value, job creation rate at minimum possible value and ISI at the current value. Note that the maximum and minimum values for emission rates, ISI and job creation is obtained through the failure analysis procedure mentioned above.

Table 7.18: Maximum and minimum value of the environmental and health indexes.

	Mininum[a]	Maximum[b]
GWP [x 10^{11} eq-t/y]	-3.56	-0.19
AP [x 10^{8} eq-t/y]	-30.39	-1.60
POCP [x 10^{9} eq-t/y]	1.49	28.28
NP [x 10^{8} eq-t/y]	3.69	70.24
ATP [x 10^{9} eq-t/y]	6.32	120.15
TTP [x 10^{8} /y]	1.25	23.68
ADP [x 10^{7} eq-t/y]	-23.06	-1.21
WF [x 10^{8} m^3/y]	4.96	94.34
HTPI [x 10^{8} /y]	1.24	23.68
HTPE [x 10^{8} /y]	3.22	61.29

[a] Value determined by multiplying the minimum emission multiplier (i.e., 1) to the current emission factor
[b] Value determined by multiplying the maximum emission multiplier (i.e., 19) to the current emission factor

Table 7.19: Description of the scenario in Figure 7.15.

<table>
<tr><th>Scenario</th><th>Emission Multiplier</th><th>ISI</th><th>JC</th></tr>
<tr><td>1</td><td>Minimum</td><td rowspan="2">Current value</td><td rowspan="6">Current value</td></tr>
<tr><td>2</td><td>Maximum</td></tr>
<tr><td>3</td><td>Minimum</td><td rowspan="2">Minimum</td></tr>
<tr><td>4</td><td>Maximum</td></tr>
<tr><td>5</td><td>Minimum</td><td rowspan="2">Maximum</td></tr>
<tr><td>6</td><td>Maximum</td></tr>
<tr><td>7</td><td>Minimum</td><td rowspan="2">Current Value</td><td rowspan="2">Minimum</td></tr>
<tr><td>8</td><td>Maximum</td></tr>
</table>

Table 7.19(cont'): Description of the scenario in Figure 7.15.

Scenario	Emission Multiplier	ISI	JC
9	Minimum	Minimum	Minimum
10	Maximum		
11	Minimum	Maximum	
12	Maximum		
13	Minimum	Current value	Maximum
14	Maximum		
15	Minimum	Minimum	
16	Maximum		
17	Minimum	Maximum	
18	Maximum		

Similarly, Figure 7.16 shows the feasible data variation range of the optimal solution for transportation design (listed in Table 7.17). If the input data (i.e., economic performance, pollutant emission, land footprint and transportation safety) for this solution falls apart from the given ranges, different optimal solution will be obtained. Again, the maximum and minimum value of the emission multiplier is used to determine the corresponding maximum and minimum value of GWP, AP, POCP, ATP, NP, TTP, ADP and HTPE (see Table 7.20). Note that the description of each scenario is given in Table 7.21.

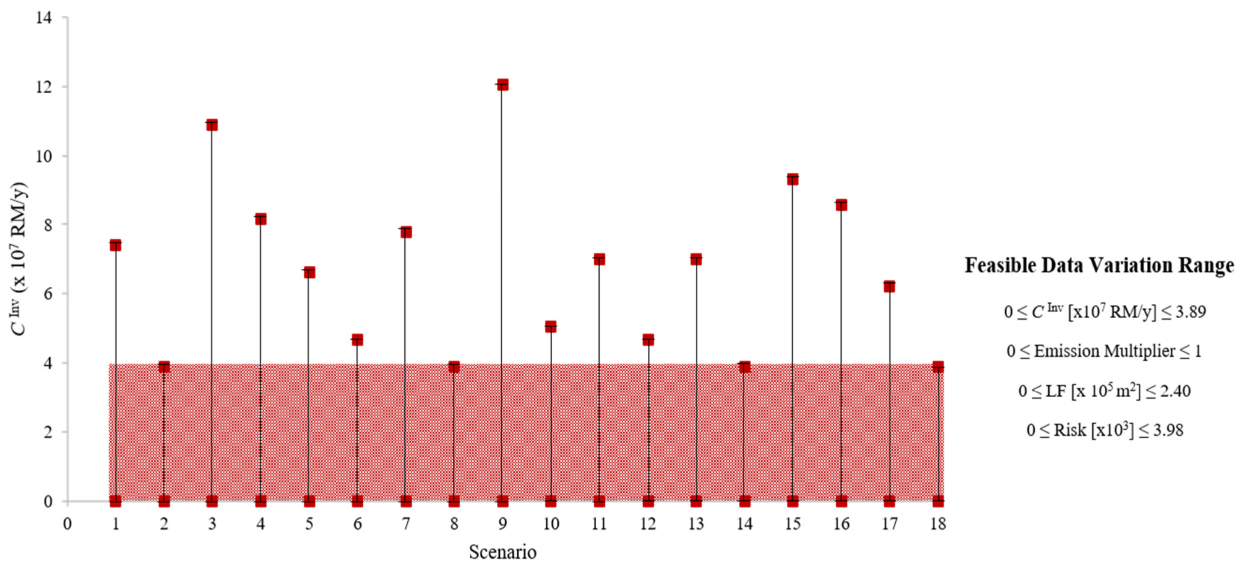

Figure 7.16: Failure Analysis (transportation design).

Table 7.20: Maximum and minimum value of the environmental and health indexes.

	Mininum[a]	Maximum[b]
GWP [x 10^7 eq-t/y]	0.00	1.02
AP [x 10^4 eq-t/y]	0.00	1.94
POCP [x 10^4 eq-t/y]	0.00	4.90
NP [x 10^3 eq-t/y]	0.00	2.22
ATP [eq-t/y]	0.00	0.02
ADP [x 10^4 eq-t/y]	0.00	6.48
HTPE [x 10^5 /y]	0.00	1.96

[a] Value determined by multiplying the minimum emission multiplier (i.e., 0) to the current emission factor

[b] Value determined by multiplying the maximum emission multiplier (i.e., 1) to the current emission factor

Table 7.21: Description of the scenario in Figure 7.16.

Scenario	Emission Multiplier	Risk	LF
1	Minimum	Current value	Current value
2	Maximum		
3	Minimum	Minimum	
4	Maximum		
5	Minimum	Maximum	
6	Maximum		
7	Minimum	Current value	Minimum
8	Maximum		
9	Minimum	Minimum	
10	Maximum		
11	Minimum	Maximum	
12	Maximum		
13	Minimum	Current value	Maximum
14	Maximum		
15	Minimum	Minimum	
16	Maximum		
17	Minimum	Maximum	
18	Maximum		

In addition, despite most of the impact categories have been covered in this approach, there are still some other social indicators which are not considered in the proposed model. Thus, by incorporating different social indicators into the model, the obtained results might be different. Table 7.22 shows a list of social indexes which are omitted in this work.

Table 7.22: Other social indicators.

Indicators	Description
Equity/ Ethical responsibility/ Labour rights/ Regulatory responsibility/ Induced job creation	These indicators are indeed important to reflect the social sustainability of the biomass industry. However, they are not considered in current pioneering stage due to the lack of information and data. Arbitrary assumption for these indicators are meaningless for the analysis.
Philanthropy responsibility	Additional studies should be carried out to determine the actual benefits of involvement in philanthropy activities.
Food-to-energy footprint (FEF)	FEF, which reflects the "fuel vs food" ethical issue, should be included in the model if food crops are used as the conversion feedstock. However, in the proposed case study, all the biomass is originated from agriculture residues and production wastes. Therefore, FEF is not considered in this work.

7.7 Conclusion

This chapter has developed a novel optimisation approach to synthesise an integrated biomass supply chain with the consideration of full spectrum of sustainability. The main contributions are sated below:

I. The mathematical model proposed in previous chapter is reworked to incorporate several social impacts (i.e., human toxicity, inherent safety in the processing plants, job creation, transportation safety) in the supply chain into the model.

II. A novel optimisation approach which incorporates the use of PCA and AHP techniques are proposed in order to optimise the sustainability performance of a biomass supply chain. This proposed approach is able to reduce the redundancy of the problem (reduce complexity) without losing too much information. This is also the first attempt to optimise the model based on PCs' scores.

III. The proposed optimisation approach is benchmarked with weighted sum approach and max-min aggregation approach, which have been abundantly utilised in other researches. The results show that PCA-aided optimisation approach is able to provide reliable and comparable results as compared to the rest.

IV. Pareto study is conducted to analyse the effect of relative priority of each objective on the technology selection and transportation design; while failure analysis is conducted to identify the feasible data variation range for the obtained optimal solution.

As mentioned in the discussions, PC scores can be used to identify the potential bottlenecks of the biomass supply chain. The effectiveness of using PCA as debottlenecking tool is further discussed in the next chapter (Chapter 8).

Chapter 8:

Challenges of Biomass Supply Chain in Malaysia:

Debottlenecking via PCA and P-graph Approaches

8.1 Introduction

Due to the extensive natural resources, Malaysia therefore poses an ideal and substantial potential for the bioenergy generation (Foo, 2015). Realising that biomass is one of the significant renewable energy source (Duić et al., 2011), the Malaysia government has implemented numerous policies and action plans in order to drive the biomass industry forward. Notably, Fifth Fuel Policy has provided five years tax exemptions and substantial tax allowance for the biomass industry investors (EPU, 2001). On the other hand, National Biomass Strategy has been undertaken to promote the use of agricultural biomass for high value products by increasing the CAPEX incentive of up to 40 % to local investors (AIM, 2013). Despite the ultimate goal in commercialising and localising the biomass industry in Malaysia has been commissioned, significant efforts must be done in order to remove the barriers that are hindering Malaysia from the attainment of sustainability goal.

To-date, numerous studies have discussed the potential bottlenecks of the biomass industry in Malaysia. For instance, due to the low mass density of biomass, it required an extensive amount of volume per mass ratios for storage and transportation (Strezov et al., 2016). This problem is further aggravated by the remote location of biomass sources in Malaysia (MIGHT, 2013). All these compounded issues make the transportation and storage become cost intensive. In addition, financial barrier arises when industry players face deficient in capital to pioneer into an industry, such as insufficient fund to procure necessary equipment, facility and technology, etc. (Tang et al., 2012). The operational components, including construction of the plant and facility, implementation and adoption of technology and the aforementioned cost intensive logistics arrangement have led to an overwhelming cost for the biomass industry (Mekhilef et al., 2011). In the recent decades, community has started to question the actual environmental performance of the production of biomass-derived products and bio-energy. For instance, the extensive land requirement for the biomass projects, which will inevitably lead to serious soil erosion and destruction of ecosystem, is one of the main environmental concern (Oh et al., 2010). Furthermore, the extensive emission of toxic gas (e.g., CO, SO_x, NO_x, etc.) from the thermo-conversion processes, will contribute to several environmental issues (including global warming, acid rain, etc.) (Asadullah, 2016). Besides, massive water requirement for harvesting and gigantic fuel consumption for transportation of biomass are the other main concern that obstruct the amendment of greener production (Wattana, 2014).

These works are admirable, but none of them has developed a systematic debottlenecking approach for the biomass industry. As already mentioned in Chapter 7, principal components (PCs) can be used as a guideline to identify the potential bottlenecks of the biomass supply chain. On the other hand, P-graph method which able to generate multiple solutions (optimal and sub-optimal) is another potential technique that can be applied as a debottlenecking approach. To-date, these techniques have yet to be implemented for debottlenecking purpose. Thus, two novel debottlenecking approaches that incorporate PCA approach and P-graph method are introduced in this chapter. The effectiveness of these proposed methods is demonstrated by using a case study in Johor. Besides, some key enablers for the future commercialisation of biomass industry in Malaysia is discussed in this chapter. This chapter is organised as follows: Section 8.2 presents the problem statement of this work. The research method used in this chapter is outlined in Section 8.3, while Section 8.4 shows the formulated mathematical model. In Section 8.5, the case study used in this work is described. It is followed by the result and discussion in Section 8.6. Finally, conclusion and future research are given towards the end of the chapter.

8.2 Problem Statement

This chapter aims to identify and remove the bottlenecks which hinder the sustainability performance of the biomass supply chain. This is done by using the proposed methods. Note that the problem can be stated as: given a set of biomass types *r* supplied from a set of sources *i* is delivered through a set of transportation modes *m* to a set of processing hubs *j*. Then, it is converted into a set of intermediates *l* and a set of products *p* via a set of technologies *t* and *t*'. Finally, products *p* will be delivered to a set of customers *k* through a set of transportation mode *m'*. The activities within the supply chain will cause a set of environmental issues *q* and a set of social impacts *u*.

8.3 Methodology

Figure 8.1 shows the research method used in this work. The sustainability performances (economic, environmnetal and social dimensions) of each possible solution is determined by using the formulated model. The bottlenecks are identified through two different approaches, where the first via PCA approach, while the second via P-graph approach. Then, a heuristic framework is used to identify potential strategies for debottlenecking. The detailed descriptions proposed debottlenecking approaches are given in the following sub-sections:

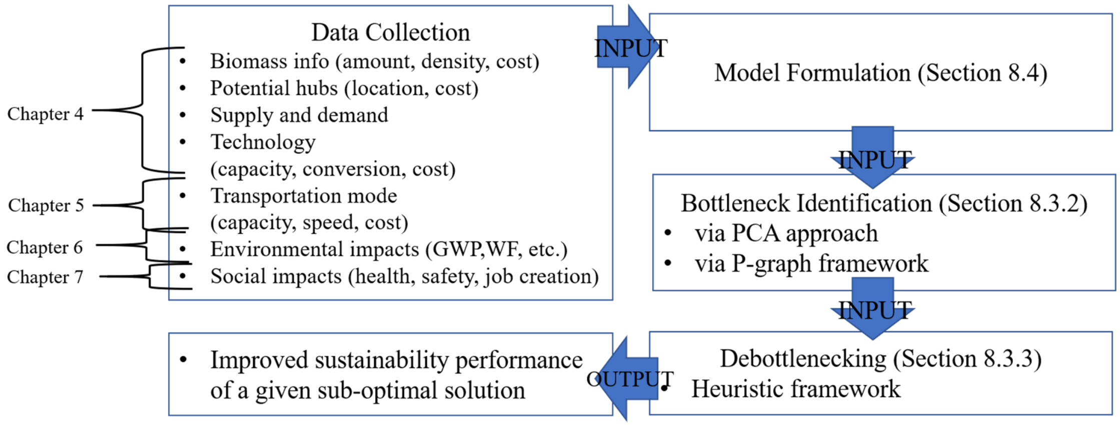

Figure 8.1: Overview of research method for Chapter 8 (reproduced from Figure 3.5).

8.3.1 Proposed Debottlenecking approaches

In this chapter, two novel debottlenecking approaches are introduced. In the first approach, PCs scores are served as indicators for bottlenecks identification; while the second approach utilise P-graph framework to target the potential bottlenecks.

8.3.1.1 Debottlenecking approach I: PCA approach

Figure 8.2 shows the flowchart for the proposed debottlenecking approach via PCA approach. Firstly, perform a PCA study to analyse all the possible solutions. Then, select one of the sub-optimal solutions that is intended to be debottlenecked. Note that the debottlenecking feasibility of each sub-optimal solution can be determined by using an evaluation method described in Section 8.3.2. The principal component (PC) scores of the selected solution are compared and benchmarked with the optimum solution (highest satisfaction). The PC that has the largest difference is notified as critical PC, while the variables that contribute a substantial portion to the PC is notified as critical variables (normally only five most contributed variables are selected). The critical variable that contributes the most will be the first potential variable to be improved. The remaining critical variables will be improved one by one according to their contribution rate (from highest to lowest), until the selected result is successfully debottlenecked (increase in ranking) or all the critical variables are analysed. To achieve this, a heuristic framework is developed to help users in proposing potential debottlenecking strategies (see Section 8.3.3). If the result is not satisfied until this stage, the entire process will be repeated by analysing another PC.

8.3.1.2 Debottlenecking approach II: P-graph approach

Figure 8.3 shows the flowchart for the proposed debottlenecking approach via P-graph approach. In this approach, the research problem is optimised by using P-graph method based on the sustainability performance. With the aid of this powerful graph-theoretic method, the optimal and sub-optimal solutions are determined simultaneously and are ranked according to the sustainability performances. Then, select one of the sub-optimal solutions that is intended to be debottlenecked (can be based on the debottlenecking feasibility analysis). The satisfactory level of each sustainability dimension of the selected solution is benchmarked with the optimal solution. The sustainability dimension that has the largest difference is notified as the potential bottleneck. The variable with the lowest satisfactory level will be the first variable to be improved. The remaining critical variables will be improved one by one according to their satisfactory level (from lowest to highest), until the selected sub-optimal solution is successfully debottlenecked (increase in ranking) or all the variables are analysed. Similar to approach I, the proposed heuristic framework in Section 8.3.3 is used to identify potential strategies for debottlenecking. If the result is not satisfied until this stage, the entire process will be repeated by analysing another dimension.

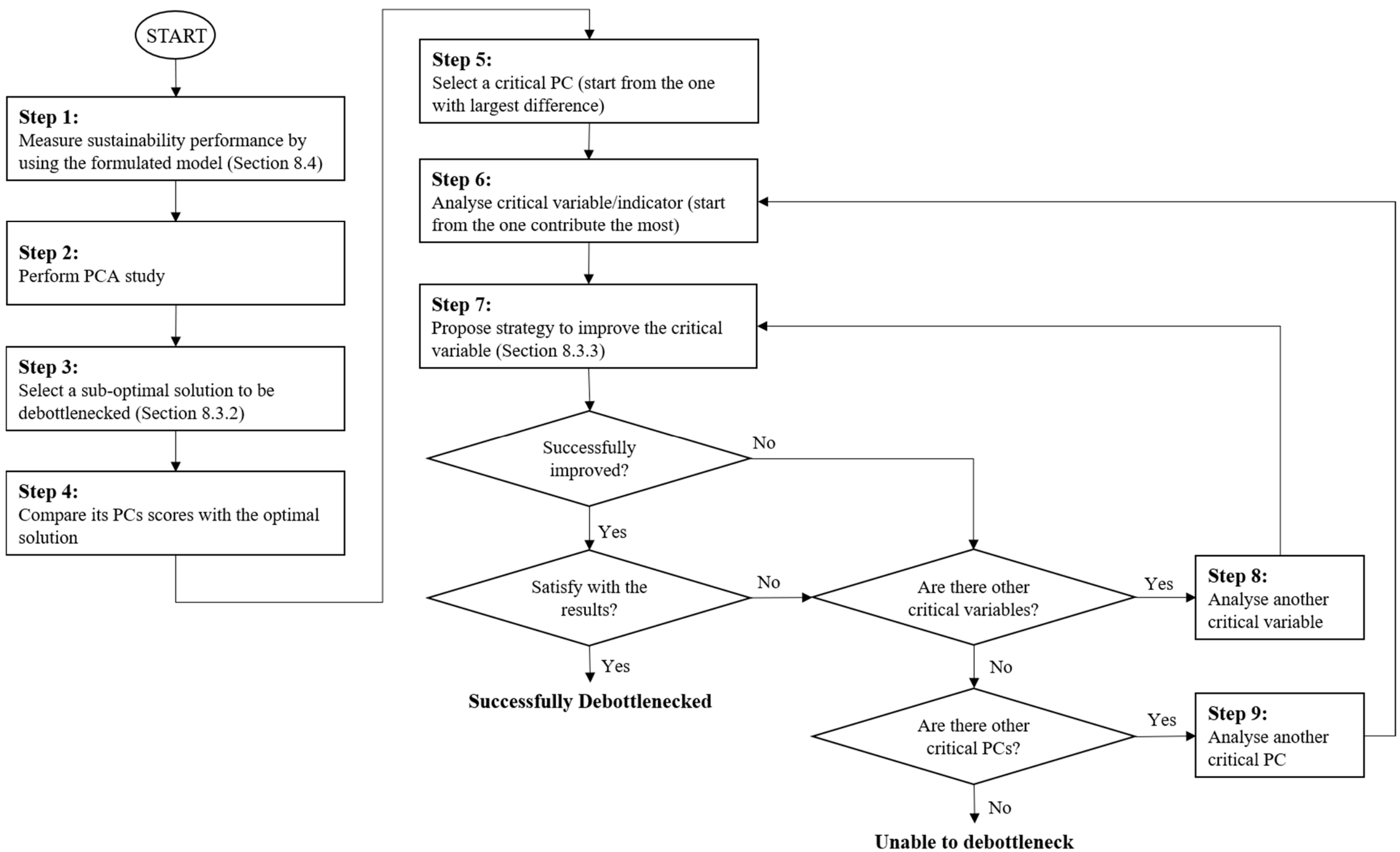

Figure 8.2: Debottlenecking process via PCA approach.

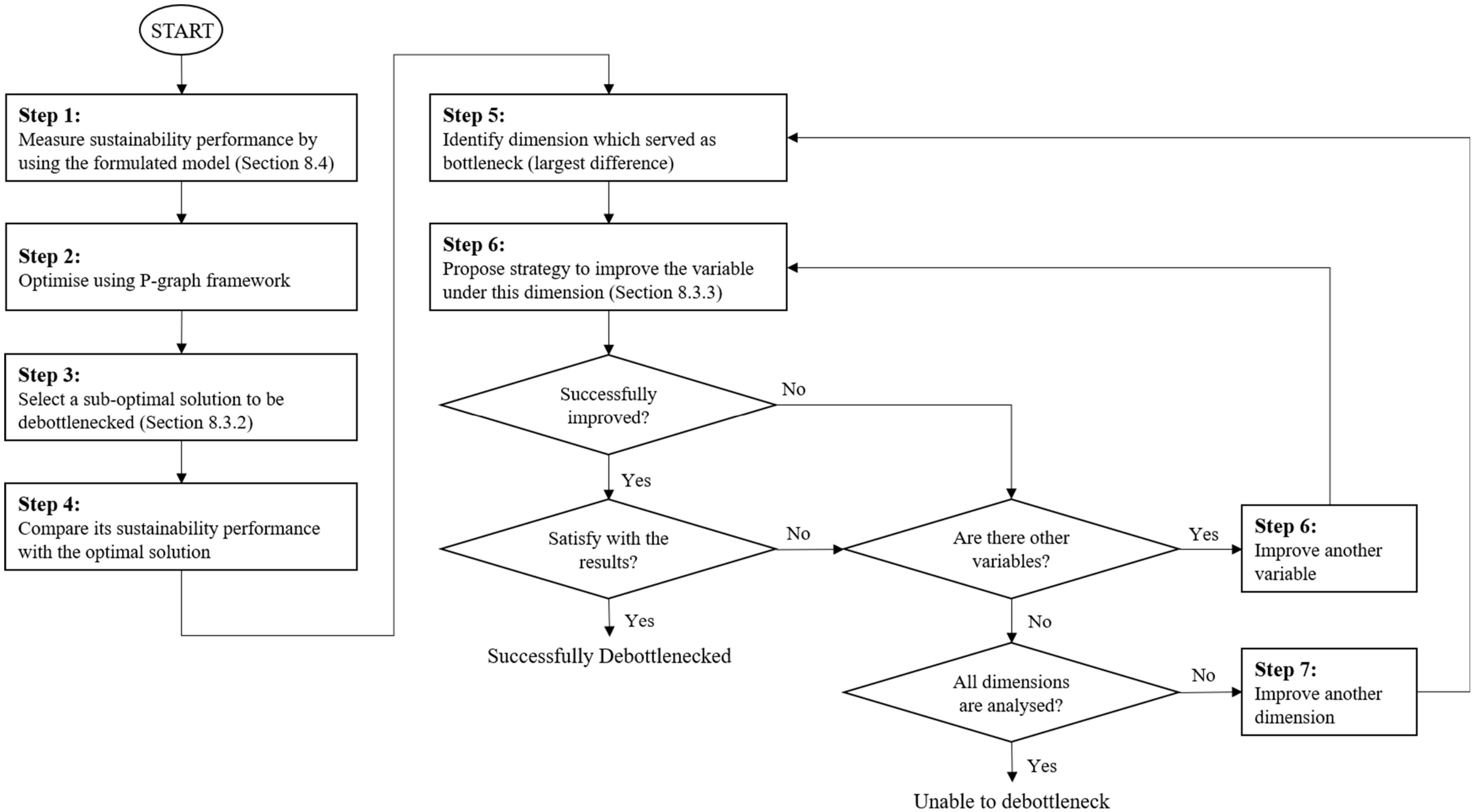

Figure 8.3: Debottlenecking process via P-graph approach.

8.3.2 Debottlenecking feasibility analysis

Debottlenecking feasibility of each sub-optimal solution is an indicator to reflect whether the respective sub-optimal solution is worth the debottlenecking effort. It is classified into three categories: High Potential (HP), Moderate Potential (MP) and Low Potential (LP). In general, HP case reflects that the performance of the respective sub-optimal solution is compatible to the optimal solution. It has a higher chance of being debottlenecked (or required less effort), following by MP case, while LP case indicates that the respective sub-optimal solution is very unlikely to be debottlenecked (or required much effort). Fundamentally, the debottlenecking attempts should start from the HP case, following by MP and LP cases. The criteria for each category is presented in Table 8.1, where $Perf^{\mathrm{Op}}$ and $Perf^{\mathrm{Sub}}$ refer to the performance of the optimal solution and sub-optimal solution respectively (i.e., λ^{SCM}).

Table 8.1: Debottlenecking feasibility analysis.

Criteria	Classification	Description
$\frac{(Perf^{\mathrm{Op}} - Perf^{\mathrm{Sub}})}{Perf^{\mathrm{Sub}}} \leq 33\ \%$	HP	Required less effort or likely to be debottlenecked
$33\ \% \leq \frac{(Perf^{\mathrm{Op}} - Perf^{\mathrm{Sub}})}{Perf^{\mathrm{Sub}}} \leq 66\ \%$	MP	Required moderate effort or less likely to be debottlenecked
$\frac{(Perf^{\mathrm{Op}} - Perf^{\mathrm{Sub}})}{Perf^{\mathrm{Sub}}} \geq 66\ \%$	LP	Required much effort or unlikely to be debottlenecked

Note that the “pinch values” (i.e., 33 %, 66 %) in this work are merely based on equal distribution. In order to improve the accuracy of the classification, these values should be tuned by analysing sufficient amount of case studies or by conducting questionnaire survey among experts from various fields. It is worth noting that this feasibility analysis is merely served as a guideline for decision-makers. In some cases, even it is classified as HP, it might still be worthless to debottleneck (e.g., especially for the declining industries or outdated products which are no longer providing positive market growth). Therefore, it is vital to incorporate other professional judgements (e.g., marketing analysis) during this analysis stage.

8.3.3 Heuristic framework for debottlenecking strategy identification

After successfully identifying the bottlenecks via the approaches introduced in Section 8.3.1, appropriate strategies have to be proposed to subsequently remove the bottlenecks. Figure 8.4 and Figure 8.5 present the heuristic framework to identify appropriate debottlenecking strategy.

First, decision-makers have to identify the possible root cause of the bottleneck (e.g., economic bottleneck can be attributed by low product yield, high transportation cost, etc.). Then, a list of questions is presented to guide decision-makers in finding the appropriate debottlenecking strategy (e.g., industry players can perform pinch analysis to reduce the energy cost). If the performance is still unsatisfied, the supply chain has to be re-analysed to identify other possible debottlenecking strategies. Aside from this, the improved supply chain design has to comply with the environmental (e.g., Environmental Quality Act 1974) and safety standard (e.g., Occupational Health and Safety Assessment (OHSAS)); else, the proposed strategy has to be modified or new strategy has to be proposed.

Moreover, feasibility test is conducted to check whether the benefit gained after debottlenecking can outweigh the effort committed. In this work, benefit-cost ratio (BCR) is used to determine the economic feasibility of the debottlenecking strategy. Note that the proposed debottlenecking strategy should be revised or rejected if BCR shows value less than 1 (Kasivisvanathan et al., 2014) or when the additional investment has exceeded the allocated budget. On the other hand, incremental ratio (IR) is analysed to evaluate worthiness of the implementation of debottlenecking strategies. It is defined in Equation (8.1), where $Perf^{\text{Before}}$ refer to the performance before debottlenecking; while $Perf^{\text{After}}$ refers to the performance after debottlenecking:

$$IR = \frac{Perf^{\text{After}} - Perf^{\text{Before}}}{Perf^{\text{Before}}} \tag{8.1}$$

If the IR exceed the threshold ratio (TR), i.e., the minimum magnitude of improvement that have to be met in order to get approval on the proposed debottlenecking strategy. The value of TR is set based on the decision-makers' preference. Note that the aforementioned IR, BCR and budget constraints are the call-off mechanisms embedded in this heuristic framework. By having these call-off mechanisms in placed, decision-makers could avoid unnessary losses and worthless investment. Besides, it may happen that the identified bottlenecks are unable to be removed. This is possible when the current research knowledge, technology and budget are not sufficient to debottleneck the supply chain.

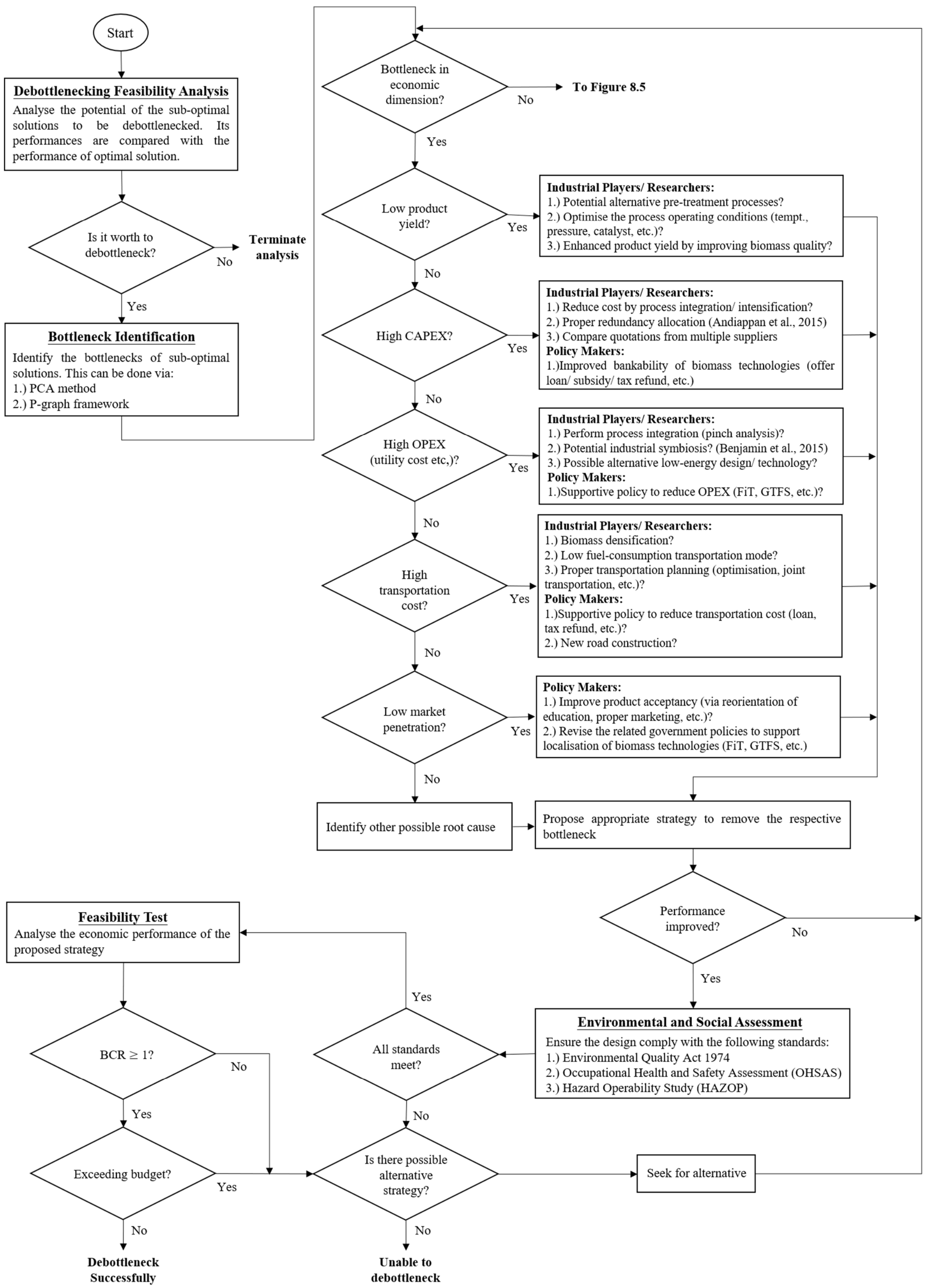

Figure 8.4: Heuristic framework for debottlenecking strategy identification (Part 1).

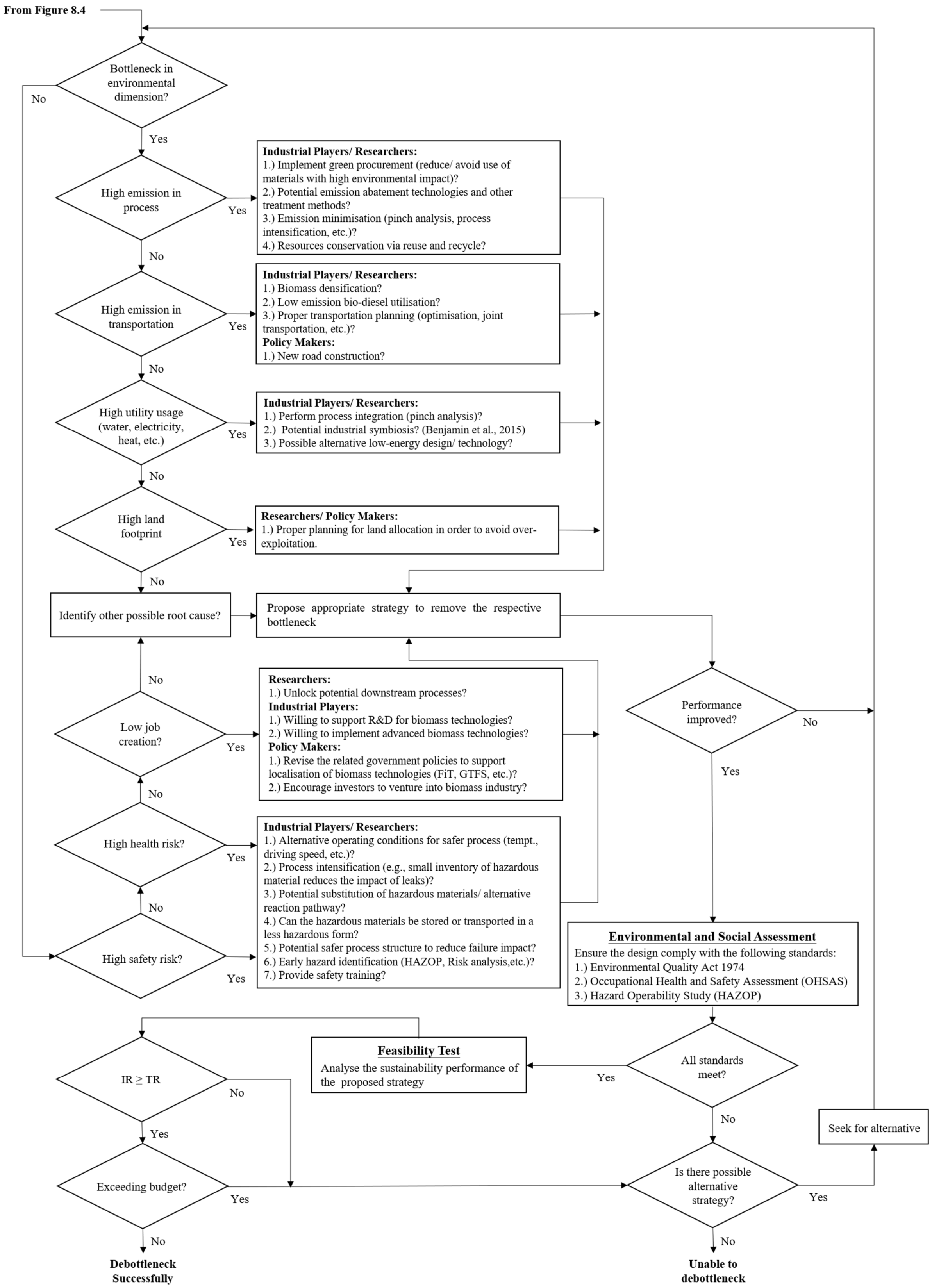

Figure 8.5: Heuristic framework for debottlenecking strategy identification (Part 2).

8.4 Model Formulation

The problem is modelled through mixed integers linear programming (MILP) and will be solved by using Lingo v14.0 (Lingo, 2015). It is formulated according to the subsections below:

8.4.1 Economic, environmental and social performances

The evaluation of each sustainability dimension is adopted from the previous chapters. Please refer to Chapter 7 for the detailed descriptions and calculations.

8.4.2 Optimisation approach

Optimisation is carried out in order to rank the possible solution according to the performance of objective function (i.e., sustainability performances).

8.4.2.1 Debottlenecking approach I: PCA approach

For debottlenecking approach I, the conventional weighted-sum approach is used to rank the possible solution based on the overall sustainability performance. Please refer to the previous chapter for the detailed descriptions of the mathematical formulation for this multi-objective optimisation approach (see Section 7.4.4.1).

8.4.2.2 Debottlenecking approach II: P-graph approach

For debottlenecking approach II, instead of using the conventional mathematical programming method, P-graph model is built to optimise the proposed problem. The P-graph model is structured in the form of weighted sum model (i.e., Equation (7.21)). Figure 8.6 shows an example P-graph model.

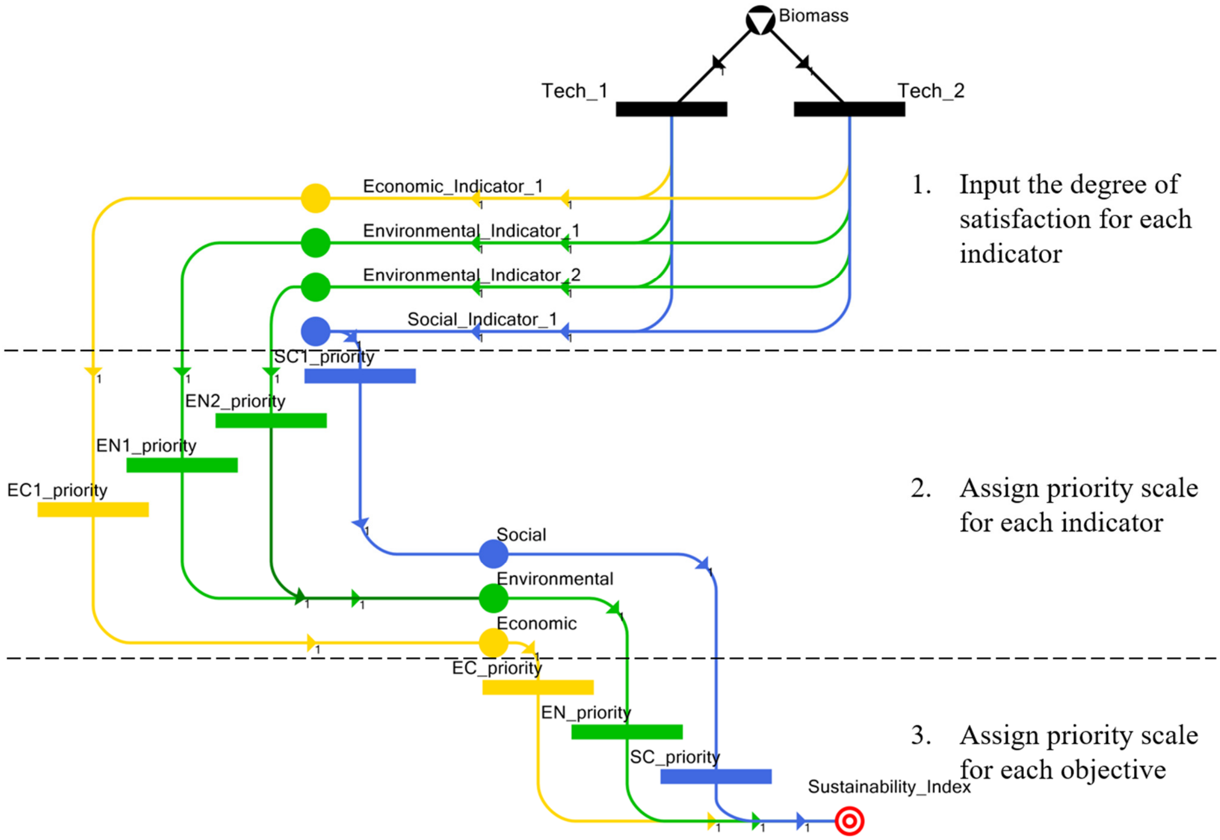

Figure 8.6: Example of P-graph model used for debottlenecking.

The construction of P-graph model can be divided into three subsequent steps. Firstly, the determined satisfaction level of each indicator is input to the model. Then, O-type vertices (horizontal bar) is used to represent the priority scale assigned to each indicator. To illustrate, since each indicator under the same sustainability dimension is assumed equally important, a conversion ratio of 0.5 is therefore set in the O-type vertices for the two environmental indicators. Subsequently, priority scale for each sustainability objective (refer to Table 7.5) which determined from AHP is inserted into the O-type vertices (in the bottom column). These priority scales can be altered by the decision-makers according to their personal preferences.

8.5 Case Study Description

A case study in Johor state is used to demonstrate the proposed debottlenecking approaches. In order to provide a clear elucidation of the effectiveness of the approaches, this work focuses on the EFB-based supply chain. In this work, 6 palm oil mills (see Figure 8.7), 25 potential processing hubs (refer to Figure 4.12), 3 possible technologies (i.e., gasification, DLF production and combustion) and 5 available transportation modes (refer to Section 5.6.4) are considered. Similar to the previous Chapter 7, this case study is also decomposed into two stages: (i) technology selection, and (ii) transportation design. Please refer to the previous chapters for detailed description for economic data, environmental data and social data used in the case study.

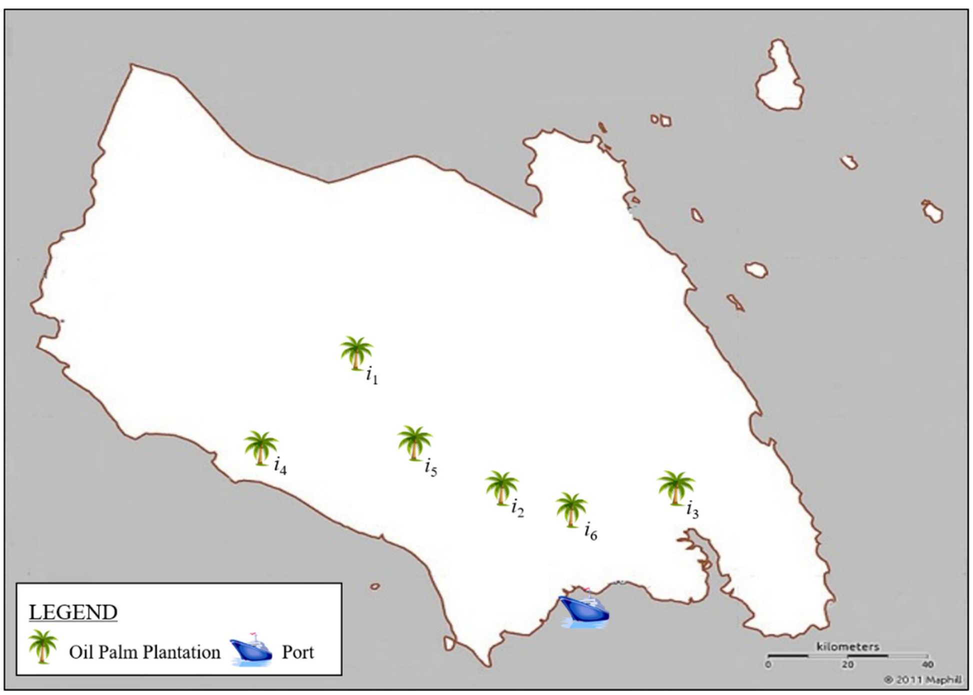

Figure 8.7: Geographical location of biomass source (Maphill, 2013).

8.6 Result and Discussion

As already mentioned, the demonstrated case study is decomposed into two stages, i.e., (i) technology selection (which aims to determine the optimal technology pathway) and (ii) transportation design (which aims to determine the optimal biomass allocation design and processing hub location). The bottlenecks of each stage are identified by using the two proposed debottlenecking approaches:

8.6.1 Technology selection

8.6.1.1 Debottlenecking approach I: PCA approach

The sustainability performances (economic, environmental and social) of each solution is determined by using the formulated model. Then, this data series are processed through PCA. As shown in Figure 8.8, PC1 and PC2 are sufficient to describe the data (since $\sum_{z=2} VAR_z > 90\ \%$). The PCs scores of each solution is tabulated in Table 8.2. Despite DLF production is categorised as HP, it is still not preferable since the DLF industry is currently depleting (MIGHT, 2013)). Therefore, in this illustration, EFB combustion which falls on LP category is then selected to be debottlenecked.

Figure 8.9 shows the contribution rate of each indicators on each PC. By comparing the PCs scores for combustion to the currently optimal solution (i.e., gasification), it can be clearly seen that PC1 is the critical PC (differs the most), while profit and ISI are the two critical variables for PC1 (high contribution rate). Note that other indicators are not considered due to the insignificance (contribution less than 5 %). Since both technologies have a similar high ISI scores (i.e., above 30) due to the nature of the process (operate under high-temperature and high-pressure condition), therefore safety aspect is not the bottleneck for this case. In term of economic dimension, gasification technology poses an ideal position compared to biomass combustion.

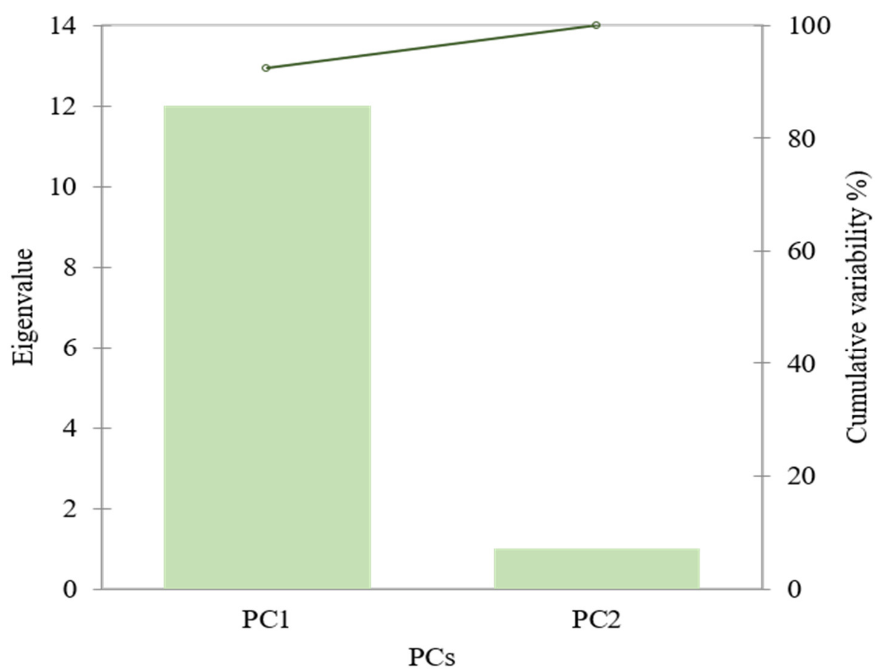

Figure 8.8: PCA for technology selection (XLSTAT, 2017).

Table 8.2: PC scores before debottlenecking (technology selection).

Technology	PC1	PC2	λ^{SCM}*	Rank*	Classification
Gasification	3.996	-0.056	0.659	1	-
DLF Production	-2.166	-0.968	0.574	2	HP
Combustion	-1.831	1.024	0.297	3	LP

*According to the total scores obtained using Equation (7.21).

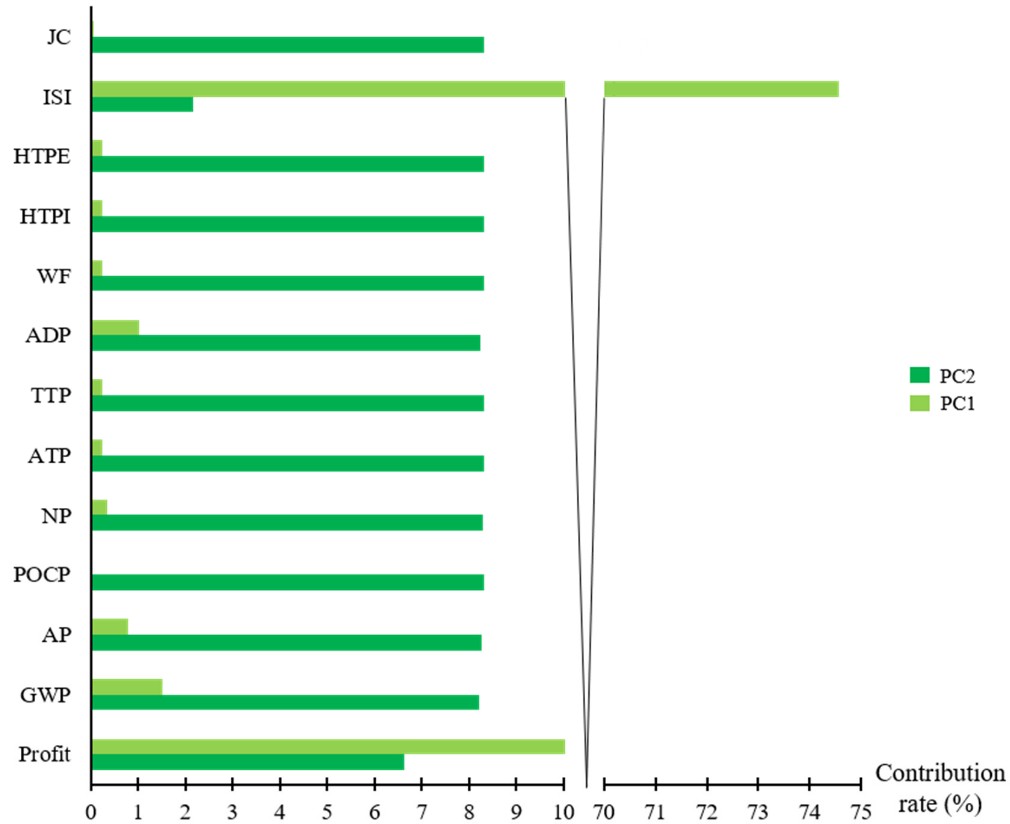

Figure 8.9: Contribution rate of each indicator (technology selection).

By using the heuristic framework presented in Figure 8.4 and Figure 8.5, it can be found that low market penetration of bio-electricity is the root cause of this economic barrier. Literature shows that this economic-unfavorability of biomass combustion is often due to the massive and continuous governmental support for the conventional energy source (Foo, 2015). Therefore, regulatory amendments should be carried out in order to advocate the development of biomass industry. The proposed debottlenecking strategy is listed in Table 8.3. This strategy requires policy makers to revise the related energy policy in order to make the bioelectricity become price-competitive compared to the conventional energy. Note that the ranking of each technology is tabulated in

Table 8.4. It shows that combustion technology is successfully debottlenecked (ranking increased while BCR>1).

Table 8.3: Proposed debottlenecking strategy (technology selection).

Criteria	Current	Proposed Strategy
Feed-in-Tariff (FiT)	<10 MW: RM0.31/kWh 10-20 MW: RM0.29/kWh 20-30 MW: RM0.27/kWh	Increase 50 %
Government Support for Fossil Energy	Subsidies, incentives and tax reduction	Eliminated
Remarks	-	Electricity cost from imported energy is assumed doubled.

Table 8.4: Rank for each technology after debottlenecking.

Technology	Rank*
Gasification	2
DLF Production	3
Combustion	1

*According to the total scores obtained using Equation (7.21).

8.6.1.2 Debottlenecking approach II: P-graph approach

The maximal structure for technology selection is built by using P-Graph Studio v5.2.0.7 (P-Graph Studio, 2017) and is illustrated as Figure 8.10. The degree of satisfaction of each variable (i.e., C^{GP}, GWP, etc.) is determined by using the mathematical model developed previously, and is input to the P-graph model. The model is then optimised by using the ABB algorithm in P-graph studio. All possible solutions (optimal and sub-optimal) are generated simultaneously and is ranked according to the sustainability performances (see Table 8.5).

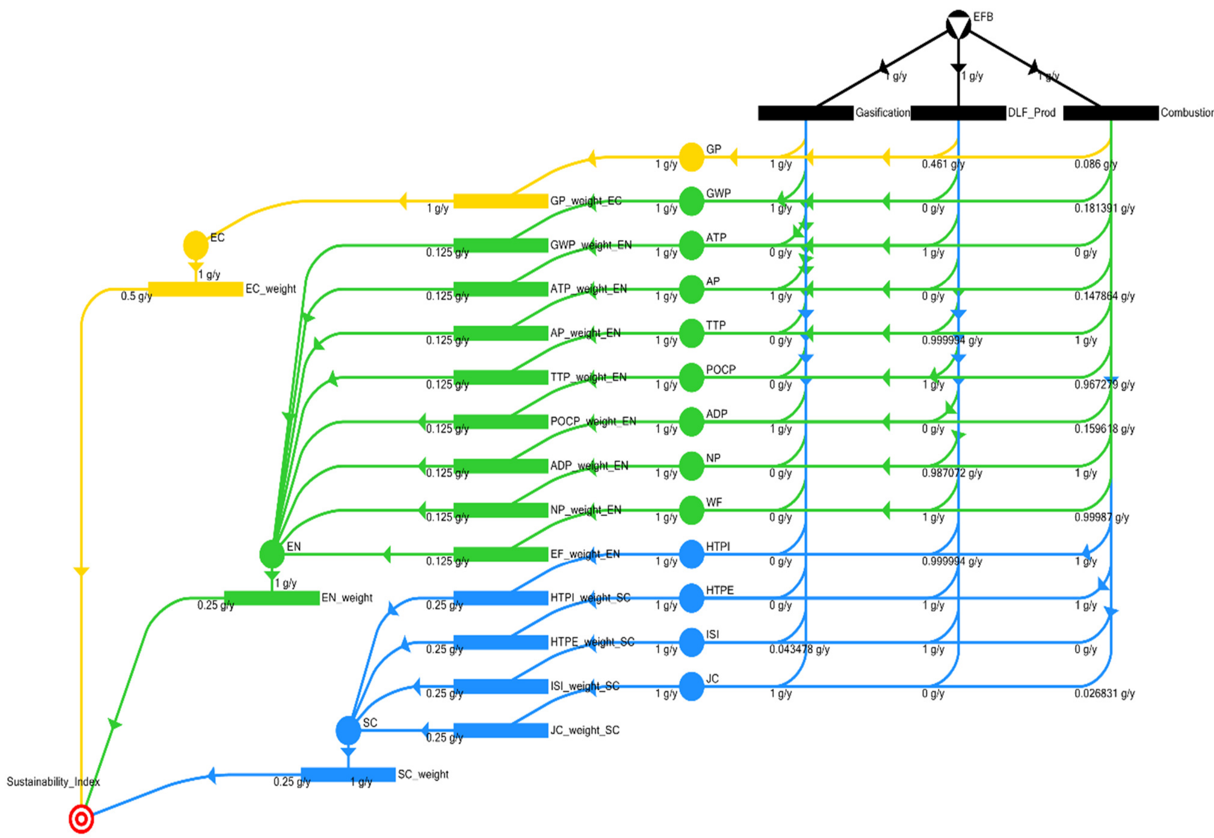

Figure 8.10: Maximal structure (technology selection).

Table 8.5: Performance and ranking of each technology (before debottlenecking).

Technology	λ^{Ec}	λ^{En}	λ^{Sc}	λ^{SCM}	Rank	Classification
Gasification	1.000	0.375	0.261	0.659	1	-
DLF Production	0.461	0.623	0.750	0.574	2	HP
Combustion	0.000	0.682	0.507	0.297	3	LP

Similarly, the results also show that economic sustainability is the key barrier for combustion technology, as λ^{Ec} of combustion technology is lower compared to gasification (current optimal solution). Therefore, after implemented the same debottlenecking strategy suggested in Table 8.3, the P-graph model is updated with the new degree of satisfaction of each variable (see Table 8.6). The graphical illustrations of the optimal solution obtained before and after debottlenecking are shown in Figure 8.11 and Figure 8.12.

Table 8.6: Performance and ranking of each technology (after debottlenecking).

Technology	λ^{Ec}	λ^{En}	λ^{Sc}	λ^{SCM}	Rank
Gasification	0.920	0.375	0.261	0.619	2
DLF Production	0.000	0.623	0.750	0.574	3
Combustion	1.000	0.682	0.507	0.7447	1

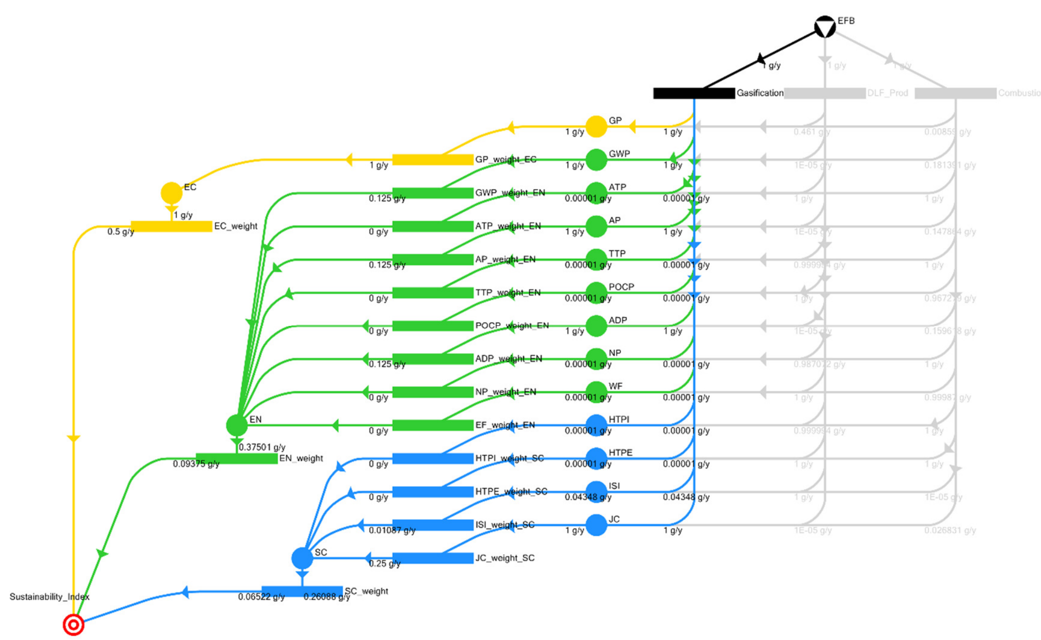

Figure 8.11: Optimal solution (before debottlenecking)

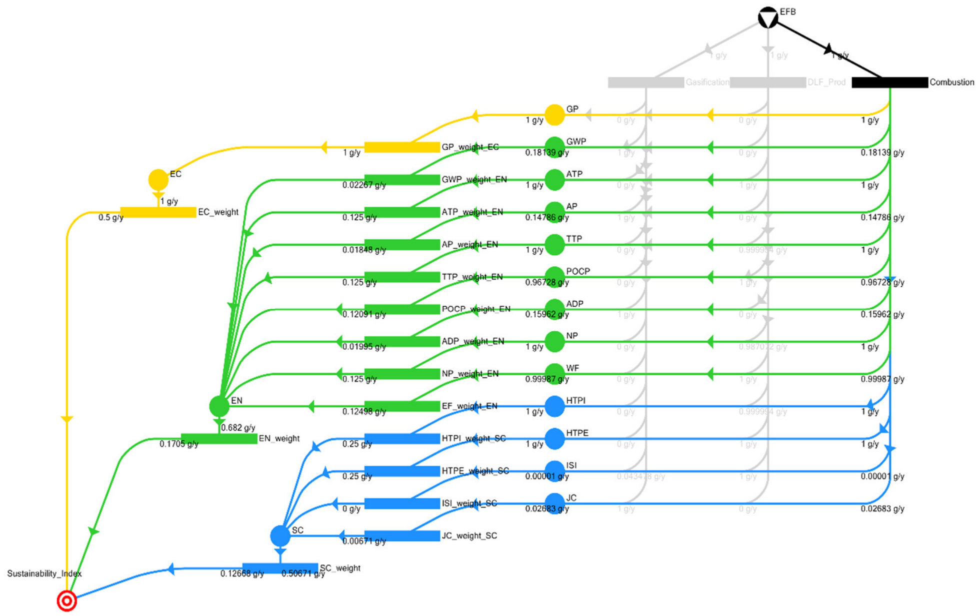

Figure 8.12: Optimal solution (after debottlenecking)

8.6.2 Transportation design

8.6.2.1 Debottlenecking approach I: PCA approach

From the previous chapters, the effect of number of processing hubs on the overall sustainability performances have already been discussed. The sustainability performances in terms of economic, environmental and social dimension of each scenario (different number of hubs) is analysed through PCA method. Figure 8.13 shows that PC1 and PC2 are sufficient to describe the data (since $\sum_{z=2} VAR_z > 90$ %). Therefore, each solution is now redefined in terms of PC1 and PC2 (see Table 8.7). Note that the PC1 and PC2 mentioned in this section is different from the one mentioned in previous section. The results show that centralised-mode (biomass from different sources are collected and processed in a central hub) is less satisfied than the decentralised-mode (biomass from different sources are processed in local).

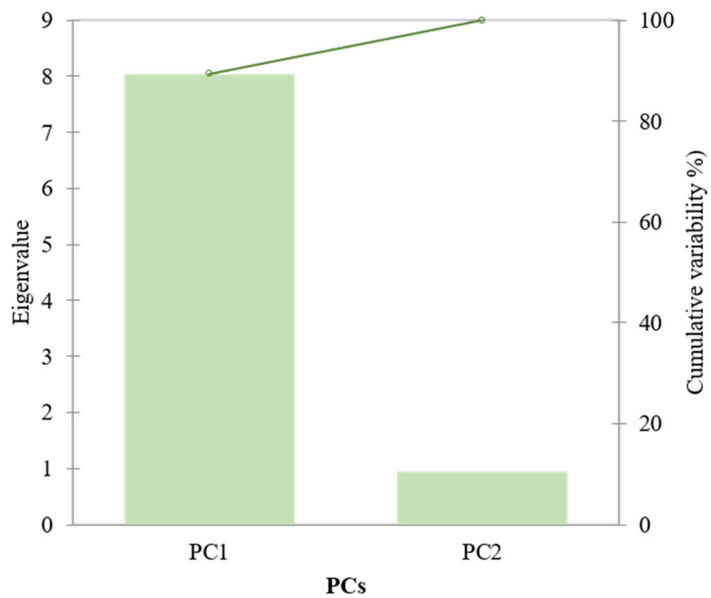

Figure 8.13: PCA for technology selection (XLSTAT, 2017).

Table 8.7: PC scores before debottlenecking (transportation design).

Design	PC1	PC2	λ^{SCM}	Rank*	Classification
Single-hub-design	4.731	0.491	0.036	5	LP
Two-hubs-design	0.523	-1.016	0.742	3	HP
Three-hubs-design	-1.323	-0.91	0.926	1	-
Four-hubs-design	-1.816	0.131	0.757	2	HP
Five-hubs-design	-2.116	1.303	0.564	4	MP

*According to the total scores obtained using Equation (7.21).

In this illustration, the two-hubs design (see Figure 8.14) which falls on HP category is selected (more likely to be debottlenecked or less effort required to made). It is benchmarked with the optimal design, i.e., three-hubs design (see Figure 8.15).

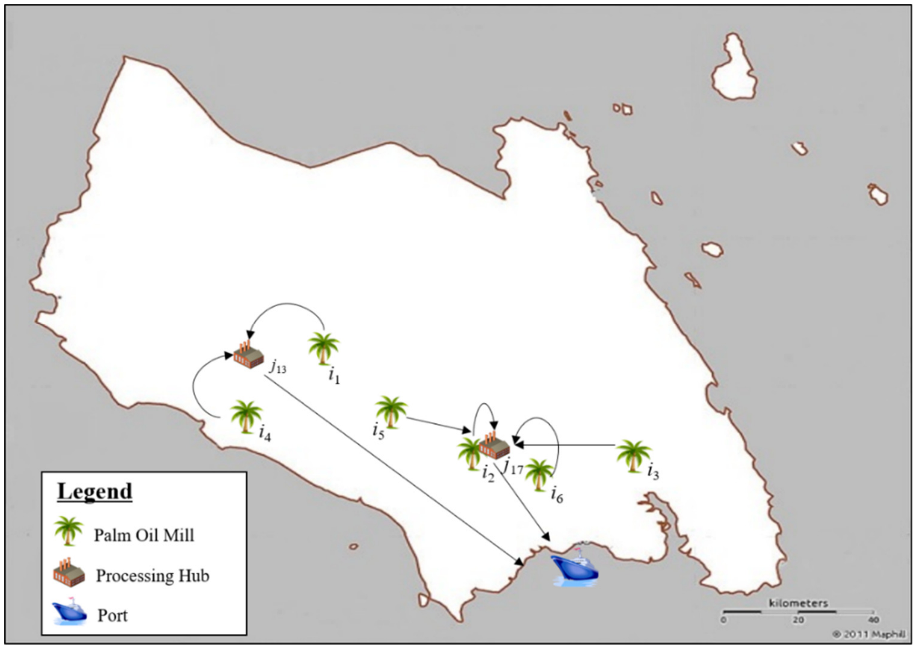

Figure 8.14: Two-hubs design.

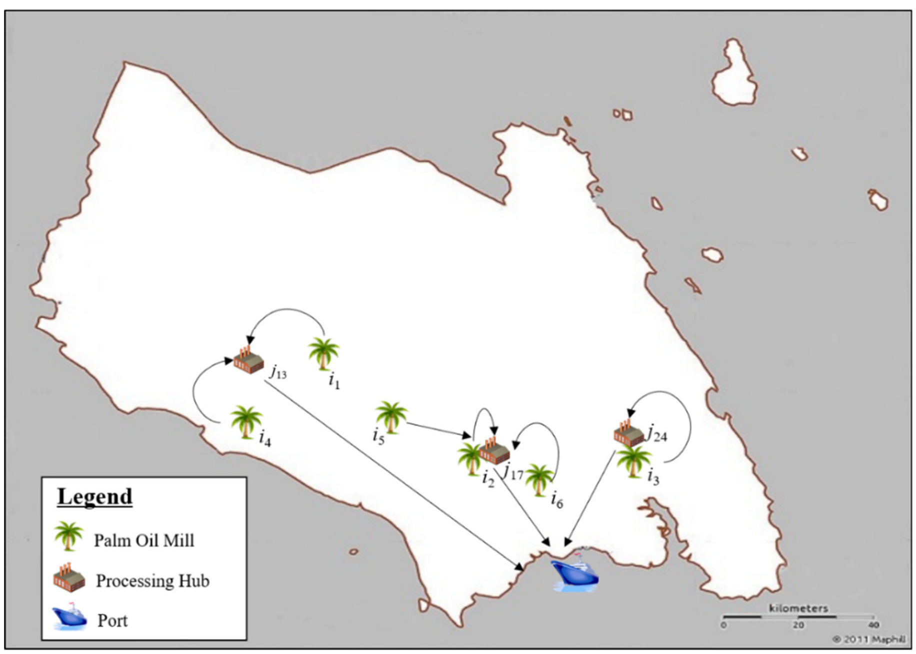

Figure 8.15: Three-hubs design.

By comparing the PCs scores for these two designs, it can be clearly seen that PC1 is the critical PC (differs the most). As shown in Figure 8.16, the critical indicators for PC1 are GWP, AP, POCP, NP, ATP, ADP and HTPE.

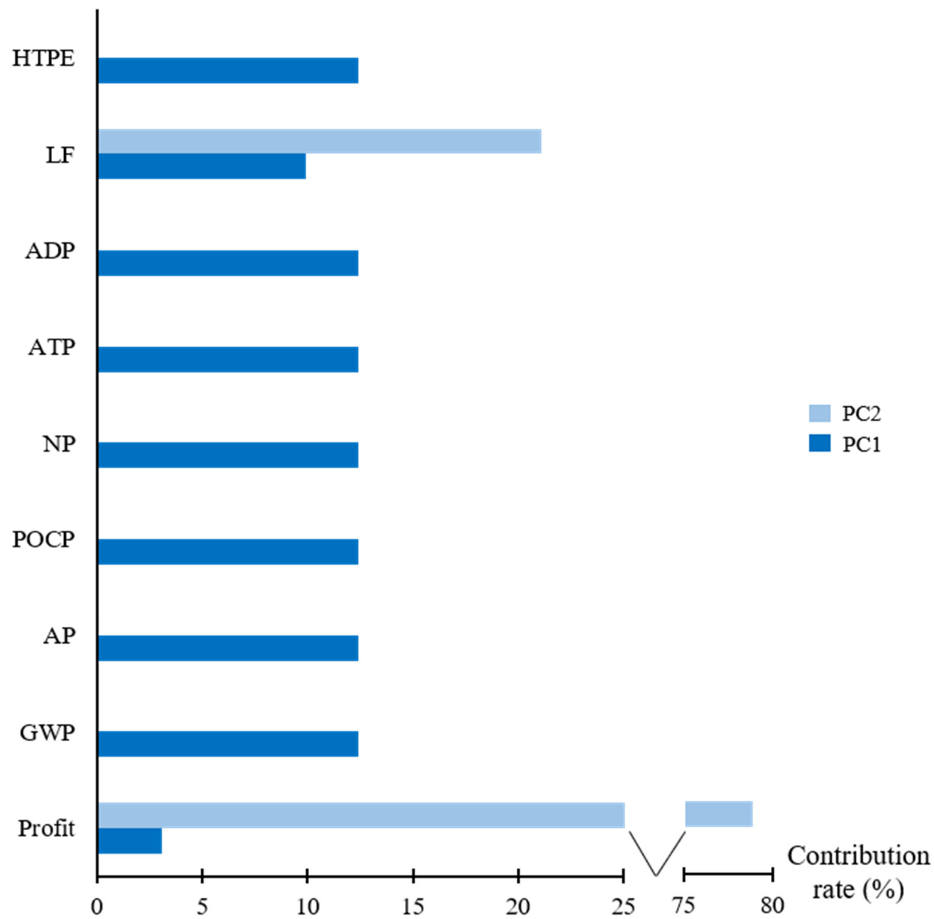

Figure 8.16: Contribution rate of each indicator (transportation design).

The high emissions of pollutants through biomass transportation are mainly attributed by the low-density nature of the biomass. According to Figure 8.4 and Figure 8.5, several debottlenecking strategies can be proposed to mitigate the environmental impacts. For instance, using environmental-benign biodiesel as a substituent transportation fuel has been proven as a promising way to reduce the emission rate.

Various studies have estimated the use of biodiesel as transportation fuel will reduce the greenhouse gas emission by 62 % (Ong et al., 2012). However, as double edge sword, the increased demand of biodiesel creates another green barrier as the harvesting of crops is driving deforestation and is likely to cause soil erosion due to the massive requirement of fertiliser (Lima et al., 2011). This will fail the feasibility test on the IR (IR<0, negative impact to the environment). Therefore, in this case study, we proposed an alternative debottlenecking strategy, i.e., pre-densification of biomass (e.g., EFB is shredded and compacted) before transportation (see Table 8.8).

Table 8.8: Proposed debottlenecking strategy (transportation design).

Criteria	Current	Strategy I	Strategy II
Pre-densification	No	No	Yes
Transportation fuel	Conventional diesel	Biodiesel	Conventional diesel
Remarks	-	Creates other environmental issues, not implemented in this work	Additional cost for pre-densification: RM20/t (AIM, 2013)
Decision	-	IR<0, Reject	Implement

As a result, the total emissions for two-hubs design are mitigated by 4.5 %, while the total transportation cost needed is decreased by 1.5 % (equivalent to RM 223,000/y), as the total number of trips required to deliver the biomass to the processing hub is reduced. The debottlenecking result is summarised in Table 8.9. Despite three processing hubs design is not the optimal solution after debottlenecking, its sustainability performances have been improved (ranking increased from third place to second place).

Table 8.9: Rank for each design after debottlenecking.

Design	λ^{SCM}	Rank*	Design	λ^{SCM}	Rank*
Single-hub-design	0.036	5	Four-hubs-design	0.768	3
Two-hubs-design	0.776	2	Five-hubs-design	0.570	4
Three-hubs-design	0.939	1			

*According to the total scores obtained using Equation (7.21).

8.6.2.2 Debottlenecking approach II: P-graph approach

Figure 8.17 shows the maximal structure for transportation design. There are five possible transportation paths in the proposed case study (i.e., number of hubs= 1, 2, 3, 4, 5). The model is then optimised by using the ABB algorithm in P-graph studio. Table 8.10 summarises the sustainability performances of each solution.

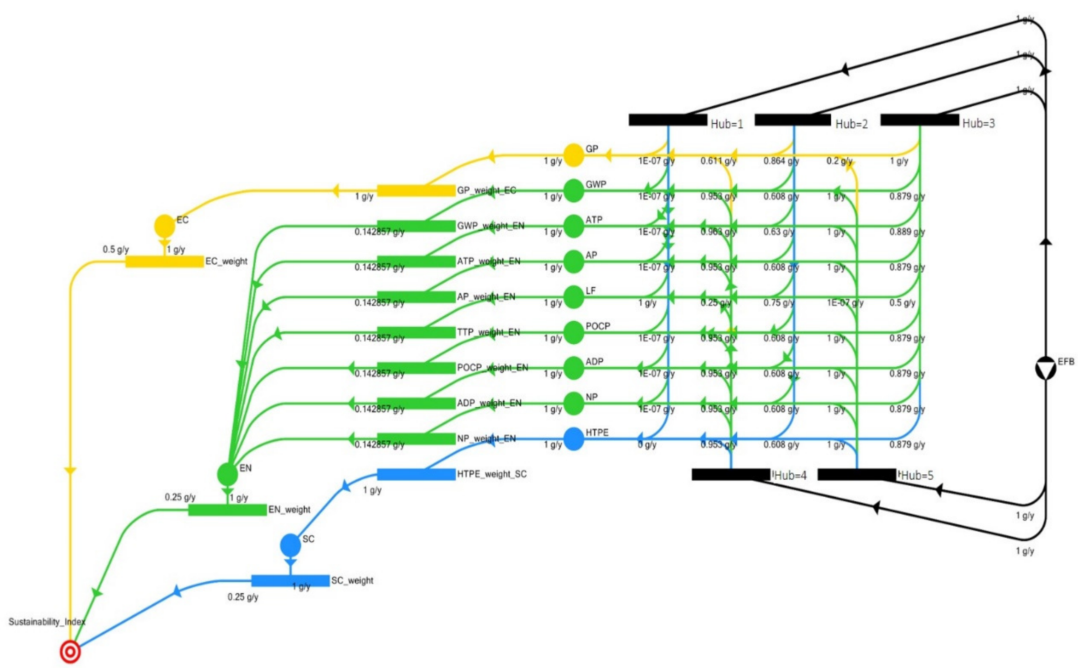

Figure 8.17: Maximal structure (transportation design).

Table 8.10: Performance and ranking of each design (before debottlenecking).

Design	λ^{Ec}	λ^{En}	λ^{Sc}	λ^{SCM}	Rank	Classification
Single-hub-design	0.000	0.143	0.000	0.036	5	LP
Two-hubs-design	0.864	0.631	0.608	0.742	3	HP
Three-hubs-design	1.000	0.826	0.879	0.926	1	-
Four-hubs-design	0.611	0.854	0.953	0.757	2	HP
Five-hubs-design	0.200	0.857	1.000	0.564	4	MP

Similar to the results obtained from PCA study, both environmental sustainability and social sustainability are the key bottlenecks for the two-hubs design (differs the most). Therefore, after implemented the same debottlenecking strategies suggested in Table 8.8, the P-graph model is updated with the new degree of satisfaction of each variable (see Table 8.11). Equivalent results are obtained for both debottlenecking approaches.

Table 8.11: Performance and ranking of each design (after debottlenecking).

Design	λ^{Ec}	λ^{En}	λ^{Sc}	λ^{SCM}	Rank
Single-hub-design	0.000	0.145	0.000	0.036	5
Two-hubs-design	0.884	0.680	0.656	0.776	3
Three-hubs-design	1.000	0.853	0.905	0.939	1
Four-hubs-design	0.623	0.864	0.963	0.768	2
Five-hubs-design	0.208	0.866	1.000	0.570	4

8.6.3 Comparison and limitation

Table 8.12 summarises the comparison of the two proposed debottlenecking approaches. In general, with the aid of the graph theoretic nature of P-graph approach, users with minimal mathematical programming background are also able to develop a rigorous model for the research problems easily and determine the optimal and sub-optimal solutions efficiently (Lam et al., 2016). In contrast, debottlenecking via PCA approach required prior algebra knowledge of the users. However, with the aid of the user-friendly closed access Excel add-ins (XLSTAT, 2017), users are able to perform PCA easily and efficiently. Aside from this, pre-processing of data is required for both approaches. The data series have to be converted into correlation matrix (covariance matrix is used if the original variables are expressed in the same unit) in order to perform PCA, whereas the degree of satisfaction (based on each index) which serves as the input data for the P-graph model, have to be pre-determined. Furthermore, the ranking of solutions has to be done manually for Approach I, while P-Graph Studio will rank all the solutions automatically for Approach II.

Table 8.12: Comparison of the proposed debottlenecking approaches.

	Approach I (PCA)	**Approach II (P-graph)**
Programming background	Basic knowledge of PCA formulation is required	Minimal knowledge is required
Pre-processing step	Data has to be converted into covariance or correlation matrix	A P-graph model has to be constructed
Ranking	Manually by users	Automatically by software
Effectiveness	Able to identify the potential bottlenecks effectively	
Limitation	Unable to reveal all the underlying bottlenecks	

Despite both approaches posed a decent performance in debottlenecking the biomass supply chain, there are some underlying bottlenecks that are unable to be identified through the simulation model. For instance, the lack of understanding of risks associated with the biomass industry (includes regulatory risk, low bankability risk, social acceptance risk) is one of the key hurdles that impedes the development of the biomass industry in Malaysia (Yatim et al., 2017). Besides, the absence of biomass monitoring and tracking system in Malaysia resulting in difficulties for robust assessments. Without these records, academicians can only show the theoretical biomass availability in their work, creating a wrong impression to the stakeholders since the actual availability and accessibility of the biomass is much less than expected (MIGHT, 2013).

In order to identify all the aforementioned bottlenecks that might be overlooked by the approaches and subsequently remove them, collaborative engagement between experts from various fields (social science, policy makers, economists, etc.) are necessary. With the aid of the in-depth studies conducted by all these experts, the stumbling blocks can now be removed in a more efficient and effective way.

8.7 Conclusion

This chapter has introduced two novel debottlenecking approaches, one through PCA method, while another through P-graph framework. The main contributions are:

I. This work presents the first attempt to pioneer these powerful techniques (PCA and P-graph) as the potential debottlenecking tools. A case study in Johor, Malaysia is used to demonstrate the effectiveness of this approach.

II. A heuristic framework is developed to help user to identify the appropriate strategies for debottlenecking.

III. The strength and limitation of the proposed approaches are discussed. It is found that collaborative engagement of experts from different fields are vital to remove the underlying bottlenecks which might be overlooked.

The demonstrated case study shows that the proposed debottlenecking approaches are applicable to debottleneck research problem efficiently. However, these approaches are still at its pioneering stage. Therefore, it should be extended into a broader framework to test the robustness of the proposed method. This can be achieved by implementing the proposed method in various research problem (e.g., water pinch problem, traveling salesman problem, etc.).

Chapter 9:

Conclusions and Future Works

9.1 Conclusions

This thesis project has illustrated a state-of-the-art philosophy for sustainability evaluation for biomass supply chain. Various streams of literatures were reviewed with respect to relevant contribution to biomass supply chain management. Based on the literature review, utilisation of biomass has been abundantly cited as a prospective solution for the sustainable development in near future. Upon review, some of the research gaps remaining in this field are outlined in Chapter 2. The main research gaps that are summarised as follow:

I. Limited works have been conducted to integrate various types of biomass into the biomass supply chain.

II. Most of the works did not consider vehicle capacity constraints during the evaluation of economic sustainability.

III. Addition efforts have to be done to integrate the indexes of three sustainability dimensions (i.e., economic, environmental and social) for the sustainability evaluation of supply chain.

IV. Lack of bottleneck detection approach that able to identify and remove the sustainability bottlenecks (not only focusing on economic factor) efficiently.

To address these research gaps, a research base case which considers multiple biomass sources, including palm based biomass (EFB and PKS), paddy biomass (rise husk and paddy straw), sugarcane bagasse and pineapple peel, is formulated. However, due to the huge problem size and complex structure of the multi-biomass supply chain, the solving efficiency has become another main concern. Thus, an innovative P-graph aided two-stage optimisation approach is introduced in Chapter 4 to gradually improve the solving efficiency. By using this proposed method, substantial amount of variables (i.e., 67 % for this case study) are reduced from the model, resulting in lower computational time.

At this stage, the transportation cost is merely determined by using a correlation cost constant, which is a similar assumption which made by most of the other works. However, this might lead to inaccurate estimation of the economic sustainability of the supply chain. Therefore, a detailed transportation design for the proposed case study is conducted in Chapter 5. In this chapter, five different transportation modes with different weight and volume constraints are considered. The comparative study that conducted in this chapter also shows that, without consideration of vehicle capacity constraints, the decision-makers will expose to the risk of getting unreliable results, causing difficulty for robust assessment and undesired loss of profit.

Thus far, economic performance is the only sustainability dimension that is used as the objective function in the optimisation model. In order to cover the full spectrum of the sustainability, the environmental sustainability indexes and social sustainability indexes have been integrated into the model in Chapter 6 and Chapter 7 respectively. AHP method, which has been widely used in other fields, is implemented to determine the priority scale of each sustainability. However, the considerations of numerous indexes intensify the model complexity and lead to redundancies in variables, resulting in difficulty for robust assessment and analysis.

In order to address this issue, a novel optimisation approach that integrates PCA method, is proposed in Chapter 7. PCA is a powerful multivariate statistical technique that able to convert complex series of variables into simpler variables representatives (i.e., principal components). Although, PCA has been abundantly used in various forms of research, it has yet to be implemented for supply chain optimisation. Due to the novelty of the concept, the optimal results obtained from this innovative optimisation approach have to be benchmarked with the results obtained from other conventional well-established optimisation approaches. The results show that PCA-aided optimisation approach is able to provide reliable and comparable results as compared to the weighted-sum approach and max-min aggregation approach. In other words, this novel approach has proven to be one of the potential optimisation approaches that should be further established and utilised in future research.

The sustainability performance of the entire biomass supply chain can now be evaluated. However, this performance is hindered by some underlying bottlenecks. To-date, the available bottleneck detection approaches are mainly aimed to detect bottlenecks (mainly refer to machines) that limit the throughput of the system (i.e., economic factor), but none of them are able to detect other bottlenecks that hinder the sustainability performances. Therefore, in order to further improve the sustainability performance of the supply chain, two debottlenecking approaches, one through PCA method while another through P-graph framework, are proposed in Chapter 8. This work presents the first attempt to pioneer these powerful techniques as the potential debottlenecking tools. The demonstrated case study shows that the proposed debottlenecking approaches are applicable to debottleneck research problem efficiently.

Aside from the aforementioned contributions, this thesis project also aims to reduce the gaps between the researchers and industry players by developing some user-friendly and non-programming-background dependent approach. The choice of introducing P-graph in Chapter 4 and Chapter 8 is not merely due to its attractive computing features (e.g., simultaneous generation of optimal and sub-optimal solutions and efficient search of solution space), but also due to its visual interface for data encoding and results display. With the aid of this graphical approach, decision-makers with minimal programming background are also able to develop or analyse their own supply chain easily, as comparable as other users with strong mathematical programming background. Similarly, SVS diagrams are developed in Chapter 5 to ease decision-makers in selecting the optimal transportation mode for their specific case directly without re-running the model. In addition, a graphical illustration method (*s*-vector) to present the sustainability performance of the results is proposed in Chapter 6. With the aid of these graphical tools, decision-makers are able to understand the insight of their problems easily and thus, robust assessment and precise decision-making can be delivered effectively.

As a whole, intensive research has been conducted on the current biomass supply chain management and several research gaps remaining has been addressed successfully in this thesis. All three objectives stated in Section 1.3 have fulfilled. This thesis covers the development of the evaluation approach of all three sustainability dimensions as well as the development of two debottlenecking approaches. A real case study in Johor state is used to demonstrate the effectiveness of each proposed method.

9.2 Future Works

As already mentioned, several research gaps have been successfully addressed in this thesis. Nevertheless, the following are some potential future works that can be conducted in order to cover the other remaining research gaps.

I. Numerous biomass available are yet to be integrated into the existing biomass supply chain (classified as underutilised biomass). The over-focus on the mainstream biomass and the lack of confidence for investors to venture in the new, unproven biomass business are often cited as the key factors that resulting in lack of driving force to exploit the value of the other potential biomass. Therefore, detailed techno-economic feasibility analysis has to be conducted for the underutilised biomass. This will provide a good biomass-business analysis platform for the investors.

II. One of the main concerns of decomposing the research problem into various sub-models during optimisation is the difficulty in ensuring global optimality of the model. For instance, the model could target the best design for the processing hubs. However, after allocating the biomass to the first plant, the remaining biomass availability might not be sufficient to support the same design in the second plant. In order to address this issue, model iterations should be conducted (see Section 4.5.4 for the example of iterations).

III. Besides, most of the biomass is high in moisture content at its origin form (> 50 wt%), resulting in higher degradability and shorter shelf life. Therefore, scheduling of the biomass storage and transportation system is another main issue that has to be addressed. In addition, the effect of time on the quality of each biomass (due to biomass degradation) has to be studied, as this will significantly affect the way the decision-makers handle the biomass.

IV. As discussed in Chapter 5, joint transportation shows significant advantageous in reducing transportation cost and mitigating emissions. However, the increase in biomass transportation flexibility will also massively increase the model size, resulting in lower solving efficiency. Therefore, there is a need to develop a systematic computational approach, which able to provide efficient search of solution space, at the same time ensure the robustness of the model.

V. In addition, the concept of SVS diagrams can be extended into a wider framework to cover other transportation paths, including railway, waterway and airway.

VI. The data used in this work is obtained from various sources (different location). Thus, the possibility of inaccuracy of data (due to different operation practice, different biomass quality, etc.) will lead to uncertainty of results. In order to address this issue, benchmarking of data should be done.

VII. Enhance the evaluation model by consideration of the omitted sustainability indexes in the latter stage of the development of biomass industry. For instance, agriculture land-use should be taken into consideration when additional land is allocated for biomass harvesting. Furthermore, in-depth studies should be conducted to determine the actual social benefits of philanthropy involvement.

VIII. On top of that, detailed plant design of the processing hub has to be conducted in order to have a better estimation on economic feasibility. This can be done by inclusion of the OPEX and CAPEX for various equipment (e.g., conveyor belts, pumps, heat exchangers, storage tanks, control room devices, firefighting systems, alarms, controllers, etc.) in the calculation.

IX. PCA-aided optimisation approach is a novel optimisation method and is still at its infancy. Thus, further verification has to be carried out to ensure its applicability and capability in solving different types of optimisation problems (e.g., water pinch problem, traveling salesman problem, etc.).

X. The two newly developed debottlenecking approaches are also at the pioneering stage. Therefore, the robustness of these approaches has to be tested by applying them in other research problems or in a larger case study. On top of that, these debottlenecking approaches can be incorporated into the conventional CQI model as both share a similar objective, i.e., to assure quality of the system.

XI. In this work, the "pinch values" used in the debottlenecking feasibility analysis are merely based on equal distribution. In order to improve the reliability of the classification, these values should be tuned by analysing sufficient amount of case studies or through questionnaire survey.

The aforementioned future works are expected to (i) improve the current research and development to have wider applications in real life; and (ii) enhance the future market penetration of biomass-derived products by having sufficient literature support and economic-feasible green technologies.

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Appendices

A.1 Appendix for Chapter 4

A.1.1 Technology selection through P-graph (Chapter 4)

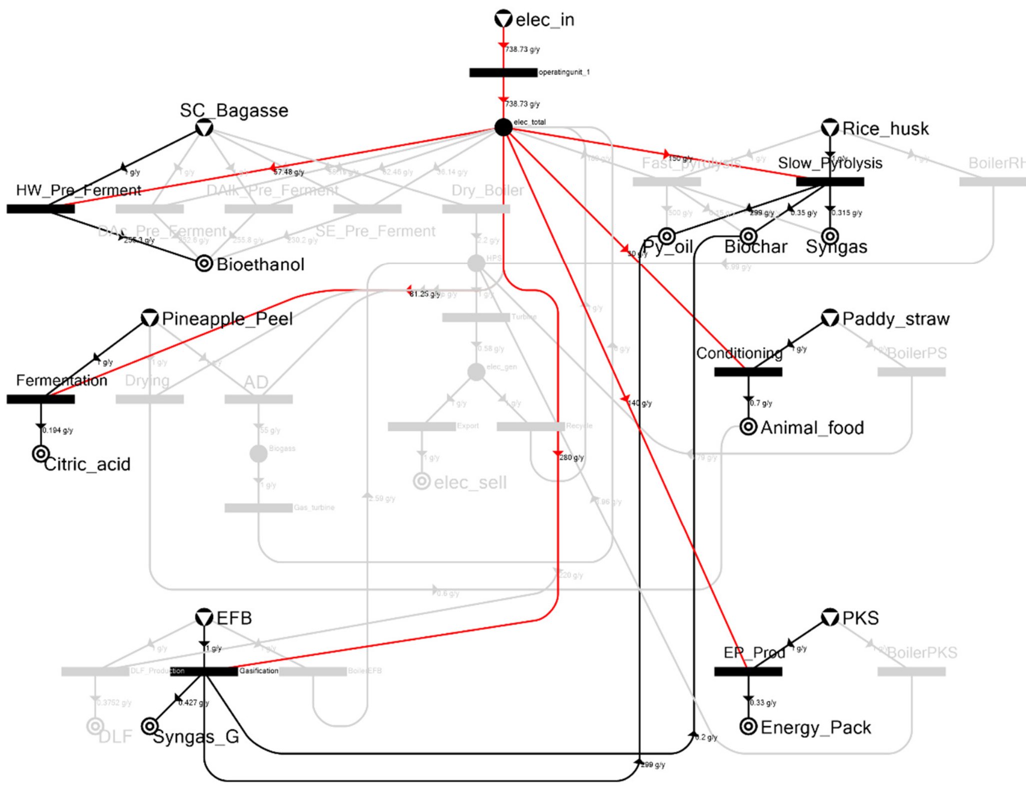

Figure A.1: Technology selection through P-graph (Chapter 4).

A.1.2 Lingo code for Chapter 4 (Base Case)

```
max=CNP;
!Source
 Sugar Cane= SC Pineapple= PA Palm Oil= PO Paddy= PD
 1=LD 2=MS 3=Muar 4=Kluang 5=JB 6=SGM 7=KJ 8=KT 9=Pont 10=BP
11=Rengam 12=SN;
SC1=1551.95;SC2=5.477;SC3=3555.377;SC4=53.115;SC5=464.755;SC6=268.894
;
SC7=243.996;SC8=99.59;PA1=555;PA3=666.5;PA4=316.5;PA6=1537;PA8=171;PA
9=155;
PO4=1174275;PO7=939420;PO8=352282.5;PO10=1051475;PO11=469710;PO12=704
565;
PD1=2769.3;PD2=2606.1;PD3=1601.4;PD4=377.4;PD10=351.9;

!hub
H1=Gemas H2=Jmentah H3=Sermin H4=Sg.Sgm H5=Tm.MS H6=Kp.Tselok.Iskd
H7=Bk.Srp H8=Bk.Gambir H9=LD H10=Muar H11=PS H12=BP H13=Ayer.Ht
```

```
H14=SB H15=SR H16=Renggam H17=Kulai H18=Pont H19=Pk.Nanas H20=Tebrau
H21=Ps.Gd H22=Kluang H23=Bd.Penawar H24=KT H25=Tenggara;
!Flow balance between source and hubs;
SC1=SC1H1+SC1H2+SC1H3+SC1H4+SC1H5+SC1H6+SC1H7+SC1H8+SC1H9+SC1H10+SC1H
11+SC1H12+SC1H13+SC1H14+SC1H15+SC1H16+SC1H17+SC1H18+SC1H19+SC1H20+SC1
H21+SC1H22+SC1H23+SC1H24+SC1H25;
SC2=SC2H1+SC2H2+SC2H3+SC2H4+SC2H5+SC2H6+SC2H7+SC2H8+SC2H9+SC2H10+SC2H
11+SC2H12+SC2H13+SC2H14+SC2H15+SC2H16+SC2H17+SC2H18+SC2H19+SC2H20+SC2
H21+SC2H22+SC2H23+SC2H24+SC2H25;
SC3=SC3H1+SC3H2+SC3H3+SC3H4+SC3H5+SC3H6+SC3H7+SC3H8+SC3H9+SC3H10+SC3H
11+SC3H12+SC3H13+SC3H14+SC3H15+SC3H16+SC3H17+SC3H18+SC3H19+SC3H20+SC3
H21+SC3H22+SC3H23+SC3H24+SC3H25;
SC4=SC4H1+SC4H2+SC4H3+SC4H4+SC4H5+SC4H6+SC4H7+SC4H8+SC4H9+SC4H10+SC4H
11+SC4H12+SC4H13+SC4H14+SC4H15+SC4H16+SC4H17+SC4H18+SC4H19+SC4H20+SC4
H21+SC4H22+SC4H23+SC4H24+SC4H25;
SC5=SC5H1+SC5H2+SC5H3+SC5H4+SC5H5+SC5H6+SC5H7+SC5H8+SC5H9+SC5H10+SC5H
11+SC5H12+SC5H13+SC5H14+SC5H15+SC5H16+SC5H17+SC5H18+SC5H19+SC5H20+SC5
H21+SC5H22+SC5H23+SC5H24+SC5H25;
SC6=SC6H1+SC6H2+SC6H3+SC6H4+SC6H5+SC6H6+SC6H7+SC6H8+SC6H9+SC6H10+SC6H
11+SC6H12+SC6H13+SC6H14+SC6H15+SC6H16+SC6H17+SC6H18+SC6H19+SC6H20+SC6
H21+SC6H22+SC6H23+SC6H24+SC6H25;
SC7=SC7H1+SC7H2+SC7H3+SC7H4+SC7H5+SC7H6+SC7H7+SC7H8+SC7H9+SC7H10+SC7H
11+SC7H12+SC7H13+SC7H14+SC7H15+SC7H16+SC7H17+SC7H18+SC7H19+SC7H20+SC7
H21+SC7H22+SC7H23+SC7H24+SC7H25;
SC8=SC8H1+SC8H2+SC8H3+SC8H4+SC8H5+SC8H6+SC8H7+SC8H8+SC8H9+SC8H10+SC8H
11+SC8H12+SC8H13+SC8H14+SC8H15+SC8H16+SC8H17+SC8H18+SC8H19+SC8H20+SC8
H21+SC8H22+SC8H23+SC8H24+SC8H25;
PA1=PA1H1+PA1H2+PA1H3+PA1H4+PA1H5+PA1H6+PA1H7+PA1H8+PA1H9+PA1H10+PA1H
11+PA1H12+PA1H13+PA1H14+PA1H15+PA1H16+PA1H17+PA1H18+PA1H19+PA1H20+PA1
H21+PA1H22+PA1H23+PA1H24+PA1H25;
PA3=PA3H1+PA3H2+PA3H3+PA3H4+PA3H5+PA3H6+PA3H7+PA3H8+PA3H9+PA3H10+PA3H
11+PA3H12+PA3H13+PA3H14+PA3H15+PA3H16+PA3H17+PA3H18+PA3H19+PA3H20+PA3
H21+PA3H22+PA3H23+PA3H24+PA3H25;
PA4=PA4H1+PA4H2+PA4H3+PA4H4+PA4H5+PA4H6+PA4H7+PA4H8+PA4H9+PA4H10+PA4H
11+PA4H12+PA4H13+PA4H14+PA4H15+PA4H16+PA4H17+PA4H18+PA4H19+PA4H20+PA4
H21+PA4H22+PA4H23+PA4H24+PA4H25;
PA6=PA6H1+PA6H2+PA6H3+PA6H4+PA6H5+PA6H6+PA6H7+PA6H8+PA6H9+PA6H10+PA6H
11+PA6H12+PA6H13+PA6H14+PA6H15+PA6H16+PA6H17+PA6H18+PA6H19+PA6H20+PA6
H21+PA6H22+PA6H23+PA6H24+PA6H25;
PA8=PA8H1+PA8H2+PA8H3+PA8H4+PA8H5+PA8H6+PA8H7+PA8H8+PA8H9+PA8H10+PA8H
11+PA8H12+PA8H13+PA8H14+PA8H15+PA8H16+PA8H17+PA8H18+PA8H19+PA8H20+PA8
H21+PA8H22+PA8H23+PA8H24+PA8H25;
PA9=PA9H1+PA9H2+PA9H3+PA9H4+PA9H5+PA9H6+PA9H7+PA9H8+PA9H9+PA9H10+PA9H
11+PA9H12+PA9H13+PA9H14+PA9H15+PA9H16+PA9H17+PA9H18+PA9H19+PA9H20+PA9
H21+PA9H22+PA9H23+PA9H24+PA9H25;
PO4=PO4H1+PO4H2+PO4H3+PO4H4+PO4H5+PO4H6+PO4H7+PO4H8+PO4H9+PO4H10+PO4H
11+PO4H12+PO4H13+PO4H14+PO4H15+PO4H16+PO4H17+PO4H18+PO4H19+PO4H20+PO4
H21+PO4H22+PO4H23+PO4H24+PO4H25;
PO7=PO7H1+PO7H2+PO7H3+PO7H4+PO7H5+PO7H6+PO7H7+PO7H8+PO7H9+PO7H10+PO7H
11+PO7H12+PO7H13+PO7H14+PO7H15+PO7H16+PO7H17+PO7H18+PO7H19+PO7H20+PO7
H21+PO7H22+PO7H23+PO7H24+PO7H25;
PO8=PO8H1+PO8H2+PO8H3+PO8H4+PO8H5+PO8H6+PO8H7+PO8H8+PO8H9+PO8H10+PO8H
11+PO8H12+PO8H13+PO8H14+PO8H15+PO8H16+PO8H17+PO8H18+PO8H19+PO8H20+PO8
H21+PO8H22+PO8H23+PO8H24+PO8H25;
PO10=PO10H1+PO10H2+PO10H3+PO10H4+PO10H5+PO10H6+PO10H7+PO10H8+PO10H9+P
O10H10+PO10H11+PO10H12+PO10H13+PO10H14+PO10H15+PO10H16+PO10H17+PO10H1
8+PO10H19+PO10H20+PO10H21+PO10H22+PO10H23+PO10H24+PO10H25;
PO11=PO11H1+PO11H2+PO11H3+PO11H4+PO11H5+PO11H6+PO11H7+PO11H8+PO11H9+P
O11H10+PO11H11+PO11H12+PO11H13+PO11H14+PO11H15+PO11H16+PO11H17+PO11H1
8+PO11H19+PO11H20+PO11H21+PO11H22+PO11H23+PO11H24+PO11H25;
```

```
PO12=PO12H1+PO12H2+PO12H3+PO12H4+PO12H5+PO12H6+PO12H7+PO12H8+PO12H9+P
O12H10+PO12H11+PO12H12+PO12H13+PO12H14+PO12H15+PO12H16+PO12H17+PO12H1
8+PO12H19+PO12H20+PO12H21+PO12H22+PO12H23+PO12H24+PO12H25;
PD1=PD1H1+PD1H2+PD1H3+PD1H4+PD1H5+PD1H6+PD1H7+PD1H8+PD1H9+PD1H10+PD1H
11+PD1H12+PD1H13+PD1H14+PD1H15+PD1H16+PD1H17+PD1H18+PD1H19+PD1H20+PD1
H21+PD1H22+PD1H23+PD1H24+PD1H25;
PD2=PD2H1+PD2H2+PD2H3+PD2H4+PD2H5+PD2H6+PD2H7+PD2H8+PD2H9+PD2H10+PD2H
11+PD2H12+PD2H13+PD2H14+PD2H15+PD2H16+PD2H17+PD2H18+PD2H19+PD2H20+PD2
H21+PD2H22+PD2H23+PD2H24+PD2H25;
PD3=PD3H1+PD3H2+PD3H3+PD3H4+PD3H5+PD3H6+PD3H7+PD3H8+PD3H9+PD3H10+PD3H
11+PD3H12+PD3H13+PD3H14+PD3H15+PD3H16+PD3H17+PD3H18+PD3H19+PD3H20+PD3
H21+PD3H22+PD3H23+PD3H24+PD3H25;
PD4=PD4H1+PD4H2+PD4H3+PD4H4+PD4H5+PD4H6+PD4H7+PD4H8+PD4H9+PD4H10+PD4H
11+PD4H12+PD4H13+PD4H14+PD4H15+PD4H16+PD4H17+PD4H18+PD4H19+PD4H20+PD4
H21+PD4H22+PD4H23+PD4H24+PD4H25;
PD10=PD10H1+PD10H2+PD10H3+PD10H4+PD10H5+PD10H6+PD10H7+PD10H8+PD10H9+P
D10H10+PD10H11+PD10H12+PD10H13+PD10H14+PD10H15+PD10H16+PD10H17+PD10H1
8+PD10H19+PD10H20+PD10H21+PD10H22+PD10H23+PD10H24+PD10H25;
!Amount of each biomass in each hub;
SCH1=SC1H1+SC2H1+SC3H1+SC4H1+SC5H1+SC6H1+SC7H1+SC8H1;
SCH2=SC1H2+SC2H2+SC3H2+SC4H2+SC5H2+SC6H2+SC7H2+SC8H2;
SCH3=SC1H3+SC2H3+SC3H3+SC4H3+SC5H3+SC6H3+SC7H3+SC8H3;
SCH4=SC1H4+SC2H4+SC3H4+SC4H4+SC5H4+SC6H4+SC7H4+SC8H4;
SCH5=SC1H5+SC2H5+SC3H5+SC4H5+SC5H5+SC6H5+SC7H5+SC8H5;
SCH6=SC1H6+SC2H6+SC3H6+SC4H6+SC5H6+SC6H6+SC7H6+SC8H6;
SCH7=SC1H7+SC2H7+SC3H7+SC4H7+SC5H7+SC6H7+SC7H7+SC8H7;
SCH8=SC1H8+SC2H8+SC3H8+SC4H8+SC5H8+SC6H8+SC7H8+SC8H8;
SCH9=SC1H9+SC2H9+SC3H9+SC4H9+SC5H9+SC6H9+SC7H9+SC8H9;
SCH10=SC1H10+SC2H10+SC3H10+SC4H10+SC5H10+SC6H10+SC7H10+SC8H10;
SCH11=SC1H11+SC2H11+SC3H11+SC4H11+SC5H11+SC6H11+SC7H11+SC8H11;
SCH12=SC1H12+SC2H12+SC3H12+SC4H12+SC5H12+SC6H12+SC7H12+SC8H12;
SCH13=SC1H13+SC2H13+SC3H13+SC4H13+SC5H13+SC6H13+SC7H13+SC8H13;
SCH14=SC1H14+SC2H14+SC3H14+SC4H14+SC5H14+SC6H14+SC7H14+SC8H14;
SCH15=SC1H15+SC2H15+SC3H15+SC4H15+SC5H15+SC6H15+SC7H15+SC8H15;
SCH16=SC1H16+SC2H16+SC3H16+SC4H16+SC5H16+SC6H16+SC7H16+SC8H16;
SCH17=SC1H17+SC2H17+SC3H17+SC4H17+SC5H17+SC6H17+SC7H17+SC8H17;
SCH18=SC1H18+SC2H18+SC3H18+SC4H18+SC5H18+SC6H18+SC7H18+SC8H18;
SCH19=SC1H19+SC2H19+SC3H19+SC4H19+SC5H19+SC6H19+SC7H19+SC8H19;
SCH20=SC1H20+SC2H20+SC3H20+SC4H20+SC5H20+SC6H20+SC7H20+SC8H20;
SCH21=SC1H21+SC2H21+SC3H21+SC4H21+SC5H21+SC6H21+SC7H21+SC8H21;
SCH22=SC1H22+SC2H22+SC3H22+SC4H22+SC5H22+SC6H22+SC7H22+SC8H22;
SCH23=SC1H23+SC2H23+SC3H23+SC4H23+SC5H23+SC6H23+SC7H23+SC8H23;
SCH24=SC1H24+SC2H24+SC3H24+SC4H24+SC5H24+SC6H24+SC7H24+SC8H24;
SCH25=SC1H25+SC2H25+SC3H25+SC4H25+SC5H25+SC6H25+SC7H25+SC8H25;
PAH1=PA1H1+PA3H1+PA4H1+PA6H1+PA8H1+PA9H1;
PAH2=PA1H2+PA3H2+PA4H2+PA6H2+PA8H2+PA9H2;
PAH3=PA1H3+PA3H3+PA4H3+PA6H3+PA8H3+PA9H3;
PAH4=PA1H4+PA3H4+PA4H4+PA6H4+PA8H4+PA9H4;
PAH5=PA1H5+PA3H5+PA4H5+PA6H5+PA8H5+PA9H5;
PAH6=PA1H6+PA3H6+PA4H6+PA6H6+PA8H6+PA9H6;
PAH7=PA1H7+PA3H7+PA4H7+PA6H7+PA8H7+PA9H7;
PAH8=PA1H8+PA3H8+PA4H8+PA6H8+PA8H8+PA9H8;
PAH9=PA1H9+PA3H9+PA4H9+PA6H9+PA8H9+PA9H9;
PAH10=PA1H10+PA3H10+PA4H10+PA6H10+PA8H10+PA9H10;
PAH11=PA1H11+PA3H11+PA4H11+PA6H11+PA8H11+PA9H11;
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PAH12=PA1H12+PA3H12+PA4H12+PA6H12+PA8H12+PA9H12;
PAH13=PA1H13+PA3H13+PA4H13+PA6H13+PA8H13+PA9H13;
PAH14=PA1H14+PA3H14+PA4H14+PA6H14+PA8H14+PA9H14;
PAH15=PA1H15+PA3H15+PA4H15+PA6H15+PA8H15+PA9H15;
PAH16=PA1H16+PA3H16+PA4H16+PA6H16+PA8H16+PA9H16;
PAH17=PA1H17+PA3H17+PA4H17+PA6H17+PA8H17+PA9H17;
PAH18=PA1H18+PA3H18+PA4H18+PA6H18+PA8H18+PA9H18;
PAH19=PA1H19+PA3H19+PA4H19+PA6H19+PA8H19+PA9H19;
PAH20=PA1H20+PA3H20+PA4H20+PA6H20+PA8H20+PA9H20;
PAH21=PA1H21+PA3H21+PA4H21+PA6H21+PA8H21+PA9H21;
PAH22=PA1H22+PA3H22+PA4H22+PA6H22+PA8H22+PA9H22;
PAH23=PA1H23+PA3H23+PA4H23+PA6H23+PA8H23+PA9H23;
PAH24=PA1H24+PA3H24+PA4H24+PA6H24+PA8H24+PA9H24;
PAH25=PA1H25+PA3H25+PA4H25+PA6H25+PA8H25+PA9H25;
POH1=PO4H1+PO7H1+PO8H1+PO10H1+PO11H1+PO12H1;
POH2=PO4H2+PO7H2+PO8H2+PO10H2+PO11H2+PO12H2;
POH3=PO4H3+PO7H3+PO8H3+PO10H3+PO11H3+PO12H3;
POH4=PO4H4+PO7H4+PO8H4+PO10H4+PO11H4+PO12H4;
POH5=PO4H5+PO7H5+PO8H5+PO10H5+PO11H5+PO12H5;
POH6=PO4H6+PO7H6+PO8H6+PO10H6+PO11H6+PO12H6;
POH7=PO4H7+PO7H7+PO8H7+PO10H7+PO11H7+PO12H7;
POH8=PO4H8+PO7H8+PO8H8+PO10H8+PO11H8+PO12H8;
POH9=PO4H9+PO7H9+PO8H9+PO10H9+PO11H9+PO12H9;
POH10=PO4H10+PO7H10+PO8H10+PO10H10+PO11H10+PO12H10;
POH11=PO4H11+PO7H11+PO8H11+PO10H11+PO11H11+PO12H11;
POH12=PO4H12+PO7H12+PO8H12+PO10H12+PO11H12+PO12H12;
POH13=PO4H13+PO7H13+PO8H13+PO10H13+PO11H13+PO12H13;
POH14=PO4H14+PO7H14+PO8H14+PO10H14+PO11H14+PO12H14;
POH15=PO4H15+PO7H15+PO8H15+PO10H15+PO11H15+PO12H15;
POH16=PO4H16+PO7H16+PO8H16+PO10H16+PO11H16+PO12H16;
POH17=PO4H17+PO7H17+PO8H17+PO10H17+PO11H17+PO12H17;
POH18=PO4H18+PO7H18+PO8H18+PO10H18+PO11H18+PO12H18;
POH19=PO4H19+PO7H19+PO8H19+PO10H19+PO11H19+PO12H19;
POH20=PO4H20+PO7H20+PO8H20+PO10H20+PO11H20+PO12H20;
POH21=PO4H21+PO7H21+PO8H21+PO10H21+PO11H21+PO12H21;
POH22=PO4H22+PO7H22+PO8H22+PO10H22+PO11H22+PO12H22;
POH23=PO4H23+PO7H23+PO8H23+PO10H23+PO11H23+PO12H23;
POH24=PO4H24+PO7H24+PO8H24+PO10H24+PO11H24+PO12H24;
POH25=PO4H25+PO7H25+PO8H25+PO10H25+PO11H25+PO12H25;
PDH1=PD1H1+PD2H1+PD3H1+PD4H1+PD10H1;
PDH2=PD1H2+PD2H2+PD3H2+PD4H2+PD10H2;
PDH3=PD1H3+PD2H3+PD3H3+PD4H3+PD10H3;
PDH4=PD1H4+PD2H4+PD3H4+PD4H4+PD10H4;
PDH5=PD1H5+PD2H5+PD3H5+PD4H5+PD10H5;
PDH6=PD1H6+PD2H6+PD3H6+PD4H6+PD10H6;
PDH7=PD1H7+PD2H7+PD3H7+PD4H7+PD10H7;
PDH8=PD1H8+PD2H8+PD3H8+PD4H8+PD10H8;
PDH9=PD1H9+PD2H9+PD3H9+PD4H9+PD10H9;
PDH10=PD1H10+PD2H10+PD3H10+PD4H10+PD10H10;
PDH11=PD1H11+PD2H11+PD3H11+PD4H11+PD10H11;
PDH12=PD1H12+PD2H12+PD3H12+PD4H12+PD10H12;
PDH13=PD1H13+PD2H13+PD3H13+PD4H13+PD10H13;
PDH14=PD1H14+PD2H14+PD3H14+PD4H14+PD10H14;
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PDH15=PD1H15+PD2H15+PD3H15+PD4H15+PD10H15;
PDH16=PD1H16+PD2H16+PD3H16+PD4H16+PD10H16;
PDH17=PD1H17+PD2H17+PD3H17+PD4H17+PD10H17;
PDH18=PD1H18+PD2H18+PD3H18+PD4H18+PD10H18;
PDH19=PD1H19+PD2H19+PD3H19+PD4H19+PD10H19;
PDH20=PD1H20+PD2H20+PD3H20+PD4H20+PD10H20;
PDH21=PD1H21+PD2H21+PD3H21+PD4H21+PD10H21;
PDH22=PD1H22+PD2H22+PD3H22+PD4H22+PD10H22;
PDH23=PD1H23+PD2H23+PD3H23+PD4H23+PD10H23;
PDH24=PD1H24+PD2H24+PD3H24+PD4H24+PD10H24;
PDH25=PD1H25+PD2H25+PD3H25+PD4H25+PD10H25;

!Big M determination;
M=100000000;
@Bin(B1);SCH1+PAH1+POH1+PDH1<=B1*M;
@Bin(B2);SCH2+PAH2+POH2+PDH2<=B2*M;
@Bin(B3);SCH3+PAH3+POH3+PDH3<=B3*M;
@Bin(B4);SCH4+PAH4+POH4+PDH4<=B4*M;
@Bin(B5);SCH5+PAH5+POH5+PDH5<=B5*M;
@Bin(B6);SCH6+PAH6+POH6+PDH6<=B6*M;
@Bin(B7);SCH7+PAH7+POH7+PDH7<=B7*M;
@Bin(B8);SCH8+PAH8+POH8+PDH8<=B8*M;
@Bin(B9);SCH9+PAH9+POH9+PDH9<=B9*M;
@Bin(B10);SCH10+PAH10+POH10+PDH10<=B10*M;
@Bin(B11);SCH11+PAH11+POH11+PDH11<=B11*M;
@Bin(B12);SCH12+PAH12+POH12+PDH12<=B12*M;
@Bin(B13);SCH13+PAH13+POH13+PDH13<=B13*M;
@Bin(B14);SCH14+PAH14+POH14+PDH14<=B14*M;
@Bin(B15);SCH15+PAH15+POH15+PDH15<=B15*M;
@Bin(B16);SCH16+PAH16+POH16+PDH16<=B16*M;
@Bin(B17);SCH17+PAH17+POH17+PDH17<=B17*M;
@Bin(B18);SCH18+PAH18+POH18+PDH18<=B18*M;
@Bin(B19);SCH19+PAH19+POH19+PDH19<=B19*M;
@Bin(B20);SCH20+PAH20+POH20+PDH20<=B20*M;
@Bin(B21);SCH21+PAH21+POH21+PDH21<=B21*M;
@Bin(B22);SCH22+PAH22+POH22+PDH22<=B22*M;
@Bin(B23);SCH23+PAH23+POH23+PDH23<=B23*M;
@Bin(B24);SCH24+PAH24+POH24+PDH24<=B24*M;
@Bin(B25);SCH25+PAH25+POH25+PDH25<=B25*M;

!Distance, km;

D1H1=58.5;D1H2=31.8;D1H3=72.3;D1H4=60.5;D1H5=199 ;D1H6=202 ;D1H7=32.5
;D1H8=29.3 ;D1H9=1    ;D1H10=27.4 ;D1H11=63.2 ;D1H12=86.5 ;D1H13=94.9
;D1H14=207 ;D1H15=112  ;D1H16=125  ;D1H17=152  ;D1H18=166  ;D1H19=168
;D1H20=176  ;D1H21=192  ;D1H22=113  ;D1H23=237  ;D1H24=195;D1H25=155;
D2H1=227 ;D2H2=229 ;D2H3=200 ;D2H4=213 ;D2H5=1 ;D2H6=5   ;D2H7=224 ;D
2H8=198  ;D2H9=201  ;D2H10=193  ;D2H11=154  ;D2H12=141  ;D2H13=109  ;
D2H14=98.3;D2H15=119  ;D2H16=108  ;D2H17=134  ;D2H18=172  ;D2H19=155
;D2H20=126  ;D2H21=134  ;D2H22=88.1 ;D2H23=129  ;D2H24=92 ;D2H25=137;
D3H1=84.6;D3H2=57.7;D3H3=98.3;D3H4=91.5;D3H5=193 ;D3H6=197 ;D3H7=58.4
;D3H8=41   ;D3H9=26.9 ;D3H10=1    ;D3H11=37.6 ;D3H12=52.2 ;D3H13=89.2
;D3H14=201 ;D3H15=106  ;D3H16=119  ;D3H17=146  ;D3H18=160  ;D3H19=162
;D3H20=170  ;D3H21=186  ;D3H22=106  ;D3H23=231  ;D3H24=189;D3H25=150;
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D4H1=141 ;D4H2=139 ;D4H3=136 ;D4H4=123 ;D4H5=86.1;D4H6=89.6;D4H7=139
;D4H8=113  ;D4H9=116  ;D4H10=108  ;D4H11=68.5 ;D4H12=56  ;D4H13=23
;D4H14=94.2;D4H15=34.2 ;D4H16=23   ;D4H17=81.3 ;D4H18=95.4 ;D4H19=97.
8 ;D4H20=105  ;D4H21=121;D4H22=1 ;D4H23=138  ;D4H24=89.9 ;D4H25=44.3;
D5H1=204 ;D5H2=199 ;D5H3=196 ;D5H4=183 ;D5H5=129 ;D5H6=127 ;D5H7=200
;D5H8=174  ;D5H9=176  ;D5H10=169  ;D5H11=129  ;D5H12=118  ;D5H13=86.1
;D5H14=198 ;D5H15=67.4 ;D5H16=80.3 ;D5H17=30.1 ;D5H18=48.4 ;D5H19=31
;D5H20=17.7 ;D5H21=21.8;D5H22=104  ;D5H23=73.9;D5H24=39.7;D5H25=62.8;
D6H1=30.3;D6H2=21.2;D6H3=21.9;D6H4=9   ;D6H5=211 ;D6H6=216 ;D6H7=26
;D6H8=55.1 ;D6H9=53   ;D6H10=80.8 ;D6H11=79   ;D6H12=100  ;D6H13=92.5
;D6H14=205 ;D6H15=110  ;D6H16=123  ;D6H17=149  ;D6H18=163  ;D6H19=166
;D6H20=173 ;D6H21=189 ;D6H22=111  ;D6H23=234  ;D6H24=193  ;D6H25=153;
D7H1=181 ;D7H2=235 ;D7H3=173 ;D7H4=160 ;D7H5=132 ;D7H6=130 ;D7H7=177
;D7H8=150  ;D7H9=153  ;D7H10=146  ;D7H11=106  ;D7H12=95.3 ;D7H13=63
;D7H14=164 ;D7H15=44.3 ;D7H16=57.2 ;D7H17=1.6  ;D7H18=39.7 ;D7H19=29
;D7H20=28.3 ;D7H21=44.3;D7H22=81 ;D7H23=83.6 ;D7H24=42.8 ;D7H25=30.2;
D8H1=233 ;D8H2=228 ;D8H3=225 ;D8H4=212 ;D8H5=90.3;D8H6=89  ;D8H7=229
;D8H8=203  ;D8H9=205  ;D8H10=198  ;D8H11=158  ;D8H12=148  ;D8H13=115
;D8H14=164 ;D8H15=96.5 ;D8H16=92.3 ;D8H17=43.3 ;D8H18=81.2 ;D8H19=63.
7 ;D8H20=35.5;D8H21=75.6 ;D8H22=90   ;D8H23=48.8 ;D8H24=1  ;D8H25=47;
D9H1=193 ;D9H2=188 ;D9H3=185 ;D9H4=172 ;D9H5=170 ;D9H6=169 ;D9H7=188
;D9H8=162  ;D9H9=165  ;D9H10=157  ;D9H11=117  ;D9H12=72   ;D9H13=74.7
;D9H14=187 ;D9H15=47.9 ;D9H16=64.7 ;D9H17=38.3 ;D9H18=1   ;D9H19=16.8
;D9H20=63.2;D9H21=67.6;D9H22=80.1;D9H23=124  ;D9H24=81.6 ;D9H25=63.3;
D10H1=131;D10H2=105;D10H3=122;D10H4=110;D10H5=140;D10H6=144;D10H7=106
;D10H8=73.7;D10H9=85.1;D10H10=52.1;D10H11=23.1;D10H12=1 ;D10H13=32.8;
D10H14=148;D10H15=52.2;D10H16=64.9;D10H17=93.8;D10H18=73  ;D10H19=110
;D10H20=118;D10H21=134;D10H22=53.3;D10H23=179;D10H24=137;D10H25=96.5;
D11H1=153;D11H2=147;D11H3=144;D11H4=131;D11H5=107;D11H6=111;D11H7=148
;D11H8=122 ;D11H9=124 ;D11H10=117 ;D11H11=77;D11H12=64.5;D11H13=32.1;
D11H14=115;D11H15=12.9;D11H16=1;D11H17=55.1;D11H18=61.3;D11H19=71.6;D
11H20=79.1;D11H21=95;D11H22=20.9;D11H23=140 ;D11H24=92.2;D11H25=46.6;
D12H1=190;D12H2=185;D12H3=182;D12H4=169;D12H5=135;D12H6=133;D12H7=186
;D12H8=160;D12H9=162 ;D12H10=155 ;D12H11=115;D12H12=104;D12H13=72.1;D
12H14=184;D12H15=53.4;D12H16=66.3;D12H17=10.2;D12H18=52.2;D12H19=34.8
;D12H20=20.5;D12H21=36.5;D12H22=90.1;D12H23=75.9;D12H24=45.9;D12H25=3
8.8;DH1P=235; DH2P=216; DH3P=214; DH4P=194; DH5P=137; DH6P=138;
DH7P=242; DH8P=189;  DH9P=206;  DH10P=144;  DH11P=146;  DH12P=116;
DH13P=108;  DH14P=164; DH15P=93.4; DH16P=97.7; DH17P=56.5; DH18P=64;
DH19P=60.9; DH20P=45.6; DH21P=7.7;  DH22P=130;  DH23P=48.2;
DH24P=52.9; DH25P=51.8;

!Gross Profit;
CGP=(SC1+SC2+SC3+SC4+SC5+SC6+SC7+SC8)*89.85/0.28+(PA1+PA3+PA4+PA6+PA8
+PA9)*22.84/0.2+(PO4+PO7+PO8+PO10+PO11+PO12)*61.19/0.307+(PD1+PD2+PD3
+PD4+PD10)*124.34/0.51;

!Transportation cost;
Ctr=0.8*((SC1H1+PA1H1+PD1H1)*D1H1+(SC2H1+PD2H1)*D2H1+(SC3H1+PA3H1+PD3
H1)*D3H1+(SC4H1+PA4H1+PO4H1+PD4H1)*D4H1+SC5H1*D5H1+(SC6H1+PA6H1)*D6H1
+(SC7H1+PO7H1)*D7H1+(SC8H1+PA8H1+PO8H1)*D8H1+PA9H1*D9H1+(PO10H1+PD10H
1)*D10H1+PO11H1*D11H1+PO12H1*D12H1+(SC1H2+PA1H2+PD1H2)*D1H2+(SC2H2+PD
2H2)*D2H2+(SC3H2+PA3H2+PD3H2)*D3H2+(SC4H2+PA4H2+PO4H2+PD4H2)*D4H2+SC5
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H2*D5H2+(SC6H2+PA6H2)*D6H2+(SC7H2+PO7H2)*D7H2+(SC8H2+PA8H2+PO8H2)*D8H
2+PA9H2*D9H2+(PO10H2+PD10H2)*D10H2+PO11H2*D11H2+PO12H2*D12H2+(SC1H3+P
A1H3+PD1H3)*D1H3+(SC2H3+PD2H3)*D2H3+(SC3H3+PA3H3+PD3H3)*D3H3+(SC4H3+P
A4H3+PO4H3+PD4H3)*D4H3+SC5H3*D5H3+(SC6H3+PA6H3)*D6H3+(SC7H3+PO7H3)*D7
H3+(SC8H3+PA8H3+PO8H3)*D8H3+PA9H3*D9H3+(PO10H3+PD10H3)*D10H3+PO11H3*D
11H3+PO12H3*D12H3+(SC1H4+PA1H4+PD1H4)*D1H4+(SC2H4+PD2H4)*D2H4+(SC3H4+
PA3H4+PD3H4)*D3H4+(SC4H4+PA4H4+PO4H4+PD4H4)*D4H4+SC5H4*D5H4+(SC6H4+PA
6H4)*D6H4+(SC7H4+PO7H4)*D7H4+(SC8H4+PA8H4+PO8H4)*D8H4+PA9H4*D9H4+(PO1
0H4+PD10H4)*D10H4+PO11H4*D11H4+PO12H4*D12H4+(SC1H5+PA1H5+PD1H5)*D1H5+
(SC2H5+PD2H5)*D2H5+(SC3H5+PA3H5+PD3H5)*D3H5+(SC4H5+PA4H5+PO4H5+PD4H5)
*D4H5+SC5H5*D5H5+(SC6H5+PA6H5)*D6H5+(SC7H5+PO7H5)*D7H5+(SC8H5+PA8H5+P
O8H5)*D8H5+PA9H5*D9H5+(PO10H5+PD10H5)*D10H5+PO11H5*D11H5+PO12H5*D12H5
+(SC1H6+PA1H6+PD1H6)*D1H6+(SC2H6+PD2H6)*D2H6+(SC3H6+PA3H6+PD3H6)*D3H6
+(SC4H6+PA4H6+PO4H6+PD4H6)*D4H6+SC5H6*D5H6+(SC6H6+PA6H6)*D6H6+(SC7H6+
PO7H6)*D7H6+(SC8H6+PA8H6+PO8H6)*D8H6+PA9H6*D9H6+(PO10H6+PD10H6)*D10H6
+PO11H6*D11H6+PO12H6*D12H6+(SC1H7+PA1H7+PD1H7)*D1H7+(SC2H7+PD2H7)*D2H
7+(SC3H7+PA3H7+PD3H7)*D3H7+(SC4H7+PA4H7+PO4H7+PD4H7)*D4H7+SC5H7*D5H7+
(SC6H7+PA6H7)*D6H7+(SC7H7+PO7H7)*D7H7+(SC8H7+PA8H7+PO8H7)*D8H7+PA9H7*
D9H7+(PO10H7+PD10H7)*D10H7+PO11H7*D11H7+PO12H7*D12H7+(SC1H8+PA1H8+PD1
H8)*D1H8+(SC2H8+PD2H8)*D2H8+(SC3H8+PA3H8+PD3H8)*D3H8+(SC4H8+PA4H8+PO4
H8+PD4H8)*D4H8+SC5H8*D5H8+(SC6H8+PA6H8)*D6H8+(SC7H8+PO7H8)*D7H8+(SC8H
8+PA8H8+PO8H8)*D8H8+PA9H8*D9H8+(PO10H8+PD10H8)*D10H8+PO11H8*D11H8+PO1
2H8*D12H8+(SC1H9+PA1H9+PD1H9)*D1H9+(SC2H9+PD2H9)*D2H9+(SC3H9+PA3H9+PD
3H9)*D3H9+(SC4H9+PA4H9+PO4H9+PD4H9)*D4H9+SC5H9*D5H9+(SC6H9+PA6H9)*D6H
9+(SC7H9+PO7H9)*D7H9+(SC8H9+PA8H9+PO8H9)*D8H9+PA9H9*D9H9+(PO10H9+PD10
H9)*D10H9+PO11H9*D11H9+PO12H9*D12H9+(SC1H10+PA1H10+PD1H10)*D1H10+(SC2
H10+PD2H10)*D2H10+(SC3H10+PA3H10+PD3H10)*D3H10+(SC4H10+PA4H10+PO4H10+
PD4H10)*D4H10+SC5H10*D5H10+(SC6H10+PA6H10)*D6H10+(SC7H10+PO7H10)*D7H1
0+(SC8H10+PA8H10+PO8H10)*D8H10+PA9H10*D9H10+(PO10H10+PD10H10)*D10H10+
PO11H10*D11H10+PO12H10*D12H10+(SC1H11+PA1H11+PD1H11)*D1H11+(SC2H11+PD
2H11)*D2H11+(SC3H11+PA3H11+PD3H11)*D3H11+(SC4H11+PA4H11+PO4H11+PD4H11
)*D4H11+SC5H11*D5H11+(SC6H11+PA6H11)*D6H11+(SC7H11+PO7H11)*D7H11+(SC8
H11+PA8H11+PO8H11)*D8H11+PA9H11*D9H11+(PO10H11+PD10H11)*D10H11+PO11H1
1*D11H11+PO12H11*D12H11+(SC1H12+PA1H12+PD1H12)*D1H12+(SC2H12+PD2H12)*
D2H12+(SC3H12+PA3H12+PD3H12)*D3H12+(SC4H12+PA4H12+PO4H12+PD4H12)*D4H1
2+SC5H12*D5H12+(SC6H12+PA6H12)*D6H12+(SC7H12+PO7H12)*D7H12+(SC8H12+PA
8H12+PO8H12)*D8H12+PA9H12*D9H12+(PO10H12+PD10H12)*D10H12+PO11H12*D11H
12+PO12H12*D12H12+(SC1H13+PA1H13+PD1H13)*D1H13+(SC2H13+PD2H13)*D2H13+
(SC3H13+PA3H13+PD3H13)*D3H13+(SC4H13+PA4H13+PO4H13+PD4H13)*D4H13+SC5H
13*D5H13+(SC6H13+PA6H13)*D6H13+(SC7H13+PO7H13)*D7H13+(SC8H13+PA8H13+P
O8H13)*D8H13+PA9H13*D9H13+(PO10H13+PD10H13)*D10H13+PO11H13*D11H13+PO1
2H13*D12H13+(SC1H14+PA1H14+PD1H14)*D1H14+(SC2H14+PD2H14)*D2H14+(SC3H1
4+PA3H14+PD3H14)*D3H14+(SC4H14+PA4H14+PO4H14+PD4H14)*D4H14+SC5H14*D5H
14+(SC6H14+PA6H14)*D6H14+(SC7H14+PO7H14)*D7H14+(SC8H14+PA8H14+PO8H14)
*D8H14+PA9H14*D9H14+(PO10H14+PD10H14)*D10H14+PO11H14*D11H14+PO12H14*D
12H14+(SC1H15+PA1H15+PD1H15)*D1H15+(SC2H15+PD2H15)*D2H15+(SC3H15+PA3H
15+PD3H15)*D3H15+(SC4H15+PA4H15+PO4H15+PD4H15)*D4H15+SC5H15*D5H15+(SC
6H15+PA6H15)*D6H15+(SC7H15+PO7H15)*D7H15+(SC8H15+PA8H15+PO8H15)*D8H15
+PA9H15*D9H15+(PO10H15+PD10H15)*D10H15+PO11H15*D11H15+PO12H15*D12H15+
(SC1H16+PA1H16+PD1H16)*D1H16+(SC2H16+PD2H16)*D2H16+(SC3H16+PA3H16+PD3
H16)*D3H16+(SC4H16+PA4H16+PO4H16+PD4H16)*D4H16+SC5H16*D5H16+(SC6H16+P
A6H16)*D6H16+(SC7H16+PO7H16)*D7H16+(SC8H16+PA8H16+PO8H16)*D8H16+PA9H1
6*D9H16+(PO10H16+PD10H16)*D10H16+PO11H16*D11H16+PO12H16*D12H16+(SC1H1

```
7+PA1H17+PD1H17)*D1H17+(SC2H17+PD2H17)*D2H17+(SC3H17+PA3H17+PD3H17)*D
3H17+(SC4H17+PA4H17+PO4H17+PD4H17)*D4H17+SC5H17*D5H17+(SC6H17+PA6H17)
*D6H17+(SC7H17+PO7H17)*D7H17+(SC8H17+PA8H17+PO8H17)*D8H17+PA9H17*D9H1
7+(PO10H17+PD10H17)*D10H17+PO11H17*D11H17+PO12H17*D12H17+(SC1H18+PA1H
18+PD1H18)*D1H18+(SC2H18+PD2H18)*D2H18+(SC3H18+PA3H18+PD3H18)*D3H18+(
SC4H18+PA4H18+PO4H18+PD4H18)*D4H18+SC5H18*D5H18+(SC6H18+PA6H18)*D6H18
+(SC7H18+PO7H18)*D7H18+(SC8H18+PA8H18+PO8H18)*D8H18+PA9H18*D9H18+(PO1
0H18+PD10H18)*D10H18+PO11H18*D11H18+PO12H18*D12H18+(SC1H19+PA1H19+PD1
H19)*D1H19+(SC2H19+PD2H19)*D2H19+(SC3H19+PA3H19+PD3H19)*D3H19+(SC4H19
+PA4H19+PO4H19+PD4H19)*D4H19+SC5H19*D5H19+(SC6H19+PA6H19)*D6H19+(SC7H
19+PO7H19)*D7H19+(SC8H19+PA8H19+PO8H19)*D8H19+PA9H19*D9H19+(PO10H19+P
D10H19)*D10H19+PO11H19*D11H19+PO12H19*D12H19+(SC1H20+PA1H20+PD1H20)*D
1H20+(SC2H20+PD2H20)*D2H20+(SC3H20+PA3H20+PD3H20)*D3H20+(SC4H20+PA4H2
0+PO4H20+PD4H20)*D4H20+SC5H20*D5H20+(SC6H20+PA6H20)*D6H20+(SC7H20+PO7
H20)*D7H20+(SC8H20+PA8H20+PO8H20)*D8H20+PA9H20*D9H20+(PO10H20+PD10H20
)*D10H20+PO11H20*D11H20+PO12H20*D12H20+(SC1H21+PA1H21+PD1H21)*D1H21+(
SC2H21+PD2H21)*D2H21+(SC3H21+PA3H21+PD3H21)*D3H21+(SC4H21+PA4H21+PO4H
21+PD4H21)*D4H21+SC5H21*D5H21+(SC6H21+PA6H21)*D6H21+(SC7H21+PO7H21)*D
7H21+(SC8H21+PA8H21+PO8H21)*D8H21+PA9H21*D9H21+(PO10H21+PD10H21)*D10H
21+PO11H21*D11H21+PO12H21*D12H21+(SC1H22+PA1H22+PD1H22)*D1H22+(SC2H22
+PD2H22)*D2H22+(SC3H22+PA3H22+PD3H22)*D3H22+(SC4H22+PA4H22+PO4H22+PD4
H22)*D4H22+SC5H22*D5H22+(SC6H22+PA6H22)*D6H22+(SC7H22+PO7H22)*D7H22+(
SC8H22+PA8H22+PO8H22)*D8H22+PA9H22*D9H22+(PO10H22+PD10H22)*D10H22+PO1
1H22*D11H22+PO12H22*D12H22+(SC1H23+PA1H23+PD1H23)*D1H23+(SC2H23+PD2H2
3)*D2H23+(SC3H23+PA3H23+PD3H23)*D3H23+(SC4H23+PA4H23+PO4H23+PD4H23)*D
4H23+SC5H23*D5H23+(SC6H23+PA6H23)*D6H23+(SC7H23+PO7H23)*D7H23+(SC8H23
+PA8H23+PO8H23)*D8H23+PA9H23*D9H23+(PO10H23+PD10H23)*D10H23+PO11H23*D
11H23+PO12H23*D12H23+(SC1H24+PA1H24+PD1H24)*D1H24+(SC2H24+PD2H24)*D2H
24+(SC3H24+PA3H24+PD3H24)*D3H24+(SC4H24+PA4H24+PO4H24+PD4H24)*D4H24+S
C5H24*D5H24+(SC6H24+PA6H24)*D6H24+(SC7H24+PO7H24)*D7H24+(SC8H24+PA8H2
4+PO8H24)*D8H24+PA9H24*D9H24+(PO10H24+PD10H24)*D10H24+PO11H24*D11H24+
PO12H24*D12H24+(SC1H25+PA1H25+PD1H25)*D1H25+(SC2H25+PD2H25)*D2H25+(SC
3H25+PA3H25+PD3H25)*D3H25+(SC4H25+PA4H25+PO4H25+PD4H25)*D4H25+SC5H25*
D5H25+(SC6H25+PA6H25)*D6H25+(SC7H25+PO7H25)*D7H25+(SC8H25+PA8H25+PO8H
25)*D8H25+PA9H25*D9H25+(PO10H25+PD10H25)*D10H25+PO11H25*D11H25+PO12H2
5*D12H25)+0.5*(0.4979*(POH1*DH1P+POH2*DH2P+POH3*DH3P+POH4*DH4P+POH5*D
H5P+POH6*DH6P+POH7*DH7P+POH8*DH8P+POH9*DH9P+POH10*DH10P+POH11*DH11P+P
OH12*DH12P+POH13*DH13P+POH14*DH14P+POH15*DH15P+POH16*DH16P+POH17*DH17
P+POH18*DH18P+POH19*DH19P+POH20*DH20P+POH21*DH21P+POH22*DH22P+POH23*D
H23P+POH24*DH24P+POH25*DH25P)+0.7*(PDH1*DH1P+PDH2*DH2P+PDH3*DH3P+PDH4
*DH4P+PDH5*DH5P+PDH6*DH6P+PDH7*DH7P+PDH8*DH8P+PDH9*DH9P+PDH10*DH10P+P
DH11*DH11P+PDH12*DH12P+PDH13*DH13P+PDH14*DH14P+PDH15*DH15P+PDH16*DH16
P+PDH17*DH17P+PDH18*DH18P+PDH19*DH19P+PDH20*DH20P+PDH21*DH21P+PDH22*D
H22P+PDH23*DH23P+PDH24*DH24P+PDH25*DH25P)+0.202*(SCH1*DH1P+SCH2*DH2P+
SCH3*DH3P+SCH4*DH4P+SCH5*DH5P+SCH6*DH6P+SCH7*DH7P+SCH8*DH8P+SCH9*DH9P
+SCH10*DH10P+SCH11*DH11P+SCH12*DH12P+SCH13*DH13P+SCH14*DH14P+SCH15*DH
15P+SCH16*DH16P+SCH17*DH17P+SCH18*DH18P+SCH19*DH19P+SCH20*DH20P+SCH21
*DH21P+SCH22*DH22P+SCH23*DH23P+SCH24*DH24P+SCH25*DH25P)+0.6*(PAH1*DH1
P+PAH2*DH2P+PAH3*DH3P+PAH4*DH4P+PAH5*DH5P+PAH6*DH6P+PAH7*DH7P+PAH8*DH
8P+PAH9*DH9P+PAH10*DH10P+PAH11*DH11P+PAH12*DH12P+PAH13*DH13P+PAH14*DH
14P+PAH15*DH15P+PAH16*DH16P+PAH17*DH17P+PAH18*DH18P+PAH19*DH19P+PAH20
*DH20P+PAH21*DH21P+PAH22*DH22P+PAH23*DH23P+PAH24*DH24P+PAH25*DH25P));
```

```
!Investment cost;
Cland=25000000;LT=20; i=0.1;
CRT=(i*(1+i)^LT)/((1+i)^LT-1);
Cinv=(B1+B2+B3+B4+B5+B6+B7+B8+B9+B10+B11+B12+B13+B14+B15+B16+B17+B18+
B19+B20+B21+B22+B23+B24+B25)*Cland*CRT;

!Number of hubs;
(B1+B2+B3+B4+B5+B6+B7+B8+B9+B10+B11+B12+B13+B14+B15+B16+B17+B18+B19+B
20+B21+B22+B23+B24+B25)=11;

!Net profit;
CNP=CGP-Ctr-Cinv;

@free(CNP);

End
```

A.1.3 Optimised result for Chapter 4 (Base Case)

```
Global optimal solution found.
  Objective value:                              0.8064046E+09
  Objective bound:                              0.8064046E+09
  Infeasibilities:                              0.3539026E-07
  Extended solver steps:                                0
  Total solver iterations:                            267
```

Variable	Value	Reduced Cost
CNP	0.8064046E+09	0.000000
SC1	1551.950	0.000000
SC2	5.477000	0.000000
SC3	3555.377	0.000000
SC4	53.11500	0.000000
SC5	464.7550	0.000000
SC6	268.8940	0.000000
SC7	243.9960	0.000000
SC8	99.59000	0.000000
PA1	555.0000	0.000000
PA3	666.5000	0.000000
PA4	316.5000	0.000000
PA6	1537.000	0.000000
PA8	171.0000	0.000000
PA9	155.0000	0.000000
PO4	1174275.	0.000000
PO7	939420.0	0.000000
PO8	352282.5	0.000000
PO10	1051475.	0.000000
PO11	469710.0	0.000000
PO12	704565.0	0.000000
PD1	2769.300	0.000000
PD2	2606.100	0.000000
PD3	1601.400	0.000000
PD4	377.4000	0.000000
PD10	351.9000	0.000000
SC1H1	0.000000	33.36000
SC1H2	0.000000	19.28000
SC1H3	0.000000	51.12000
SC1H4	0.000000	52.00000

SC1H5	0.000000	156.4269
SC1H6	0.000000	155.6269
SC1H7	0.000000	16.00000
SC1H8	0.000000	0.000000
SC1H9	0.000000	0.000000
SC1H10	0.000000	0.000000
SC1H11	0.000000	0.000000
SC1H12	1551.950	0.000000
SC1H13	0.000000	14.31200
SC1H14	0.000000	101.2480
SC1H15	0.000000	18.11740
SC1H16	0.000000	28.95170
SC1H17	0.000000	46.39050
SC1H18	0.000000	85.93800
SC1H19	0.000000	75.51490
SC1H20	0.000000	75.51050
SC1H21	0.000000	85.03050
SC1H22	0.000000	22.61400
SC1H23	0.000000	113.5522
SC1H24	0.000000	80.42690
SC1H25	0.000000	48.31580
SC2H1	0.000000	170.1331
SC2H2	0.000000	179.0131
SC2H3	0.000000	155.2531
SC2H4	0.000000	175.9731
SC2H5	0.000000	0.000000
SC2H6	0.000000	0.000000
SC2H7	0.000000	171.1731
SC2H8	0.000000	136.9331
SC2H9	0.000000	161.9731
SC2H10	0.000000	134.4531
SC2H11	0.000000	74.61310
SC2H12	0.000000	45.57310
SC2H13	0.000000	27.56510
SC2H14	0.000000	16.26110
SC2H15	0.000000	25.69050
SC2H16	0.000000	17.32480
SC2H17	0.000000	33.96360
SC2H18	0.000000	92.71110
SC2H19	0.000000	67.08800
SC2H20	0.000000	37.48360
SC2H21	0.000000	40.60360
SC2H22	0.000000	4.667100
SC2H23	0.000000	29.12530
SC2H24	5.477000	0.000000
SC2H25	0.000000	35.88890
SC3H1	0.000000	81.68000
SC3H2	0.000000	67.44000
SC3H3	0.000000	99.36000
SC3H4	0.000000	104.2400
SC3H5	0.000000	179.0669
SC3H6	0.000000	179.0669
SC3H7	0.000000	64.16000
SC3H8	0.000000	36.80000
SC3H9	0.000000	48.16000
SC3H10	0.000000	6.320000
SC3H11	0.000000	6.960000
SC3H12	3555.377	0.000000
SC3H13	0.000000	37.19200
SC3H14	0.000000	123.8880
SC3H15	0.000000	40.75740

SC3H16	0.000000	51.59170
SC3H17	0.000000	69.03050
SC3H18	0.000000	108.5780
SC3H19	0.000000	98.15490
SC3H20	0.000000	98.15050
SC3H21	0.000000	107.6705
SC3H22	0.000000	44.45400
SC3H23	0.000000	136.1922
SC3H24	0.000000	103.0669
SC3H25	0.000000	71.75580
SC4H1	0.000000	166.3460
SC4H2	0.000000	172.0260
SC4H3	0.000000	169.0660
SC4H4	0.000000	168.9860
SC4H5	0.000000	133.0929
SC4H6	0.000000	132.6929
SC4H7	0.000000	168.1860
SC4H8	0.000000	133.9460
SC4H9	0.000000	158.9860
SC4H10	0.000000	131.4660
SC4H11	0.000000	71.22600
SC4H12	0.000000	42.58600
SC4H13	0.000000	23.77800
SC4H14	0.000000	77.99400
SC4H15	0.000000	22.86340
SC4H16	0.000000	14.33770
SC4H17	0.000000	56.81650
SC4H18	0.000000	96.44400
SC4H19	0.000000	86.34090
SC4H20	0.000000	85.69650
SC4H21	0.000000	95.21650
SC4H22	53.11500	0.000000
SC4H23	0.000000	101.3382
SC4H24	0.000000	63.33290
SC4H25	0.000000	26.74180
SC5H1	0.000000	200.8895
SC5H2	0.000000	204.1695
SC5H3	0.000000	201.2095
SC5H4	0.000000	201.1295
SC5H5	0.000000	151.5564
SC5H6	0.000000	146.7564
SC5H7	0.000000	201.1295
SC5H8	0.000000	166.8895
SC5H9	0.000000	191.1295
SC5H10	0.000000	164.4095
SC5H11	0.000000	103.7695
SC5H12	0.000000	76.32950
SC5H13	0.000000	58.40150
SC5H14	0.000000	145.1775
SC5H15	0.000000	33.56690
SC5H16	0.000000	44.32120
SC5H17	464.7550	0.000000
SC5H18	0.000000	42.98750
SC5H19	0.000000	17.04440
SC5H20	0.000000	0.000000
SC5H21	0.000000	0.000000
SC5H22	0.000000	66.54350
SC5H23	0.000000	34.20170
SC5H24	0.000000	7.316400
SC5H25	0.000000	25.68530
SC6H1	0.000000	0.000000

SC6H2	0.000000	0.000000
SC6H3	0.000000	0.000000
SC6H4	0.000000	0.000000
SC6H5	0.000000	155.2269
SC6H6	0.000000	156.0269
SC6H7	0.000000	0.000000
SC6H8	0.000000	9.840000
SC6H9	0.000000	30.80000
SC6H10	0.000000	31.92000
SC6H11	0.000000	1.840000
SC6H12	268.8940	0.000000
SC6H13	0.000000	1.592000
SC6H14	0.000000	88.84800
SC6H15	0.000000	5.717400
SC6H16	0.000000	16.55170
SC6H17	0.000000	33.19050
SC6H18	0.000000	72.73800
SC6H19	0.000000	63.11490
SC6H20	0.000000	62.31050
SC6H21	0.000000	71.83050
SC6H22	0.000000	10.21400
SC6H23	0.000000	100.3522
SC6H24	0.000000	68.02690
SC6H25	0.000000	35.91580
SC7H1	0.000000	205.2895
SC7H2	0.000000	255.7695
SC7H3	0.000000	205.6095
SC7H4	0.000000	205.5295
SC7H5	0.000000	176.7564
SC7H6	0.000000	171.9564
SC7H7	0.000000	205.5295
SC7H8	0.000000	170.4895
SC7H9	0.000000	195.5295
SC7H10	0.000000	168.8095
SC7H11	0.000000	108.1695
SC7H12	0.000000	80.96950
SC7H13	0.000000	62.72150
SC7H14	0.000000	140.7775
SC7H15	0.000000	37.88690
SC7H16	0.000000	48.64120
SC7H17	243.9960	0.000000
SC7H18	0.000000	58.82750
SC7H19	0.000000	38.24440
SC7H20	0.000000	31.28000
SC7H21	0.000000	40.80000
SC7H22	0.000000	70.94350
SC7H23	0.000000	64.76170
SC7H24	0.000000	32.59640
SC7H25	0.000000	22.40530
SC8H1	0.000000	247.7331
SC8H2	0.000000	251.0131
SC8H3	0.000000	248.0531
SC8H4	0.000000	247.9731
SC8H5	0.000000	144.2400
SC8H6	0.000000	140.0000
SC8H7	0.000000	247.9731
SC8H8	0.000000	213.7331
SC8H9	0.000000	237.9731
SC8H10	0.000000	211.2531
SC8H11	0.000000	150.6131
SC8H12	0.000000	123.9731

SC8H13	0.000000	105.1651
SC8H14	0.000000	141.6211
SC8H15	0.000000	80.49050
SC8H16	0.000000	77.56480
SC8H17	0.000000	34.20360
SC8H18	0.000000	92.87110
SC8H19	0.000000	66.84800
SC8H20	0.000000	37.88360
SC8H21	0.000000	66.68360
SC8H22	0.000000	78.98710
SC8H23	0.000000	37.76530
SC8H24	99.59000	0.000000
SC8H25	0.000000	36.68890
PA1H1	0.000000	57.04100
PA1H2	0.000000	39.18000
PA1H3	0.000000	70.62200
PA1H4	0.000000	67.52200
PA1H5	0.000000	160.6059
PA1H6	0.000000	160.0049
PA1H7	0.000000	41.07400
PA1H8	0.000000	14.52700
PA1H9	0.000000	17.91000
PA1H10	0.000000	5.572000
PA1H11	0.000000	5.970000
PA1H12	555.0000	0.000000
PA1H13	0.000000	12.72000
PA1H14	0.000000	110.8000
PA1H15	0.000000	13.62000
PA1H16	0.000000	25.31000
PA1H17	0.000000	34.55000
PA1H18	0.000000	75.59000
PA1H19	0.000000	64.55000
PA1H20	0.000000	61.50090
PA1H21	0.000000	63.47880
PA1H22	0.000000	25.40000
PA1H23	0.000000	100.0600
PA1H24	0.000000	67.87000
PA1H25	0.000000	35.54000
PA3H1	0.000000	105.3610
PA3H2	0.000000	87.34000
PA3H3	0.000000	118.8620
PA3H4	0.000000	119.7620
PA3H5	0.000000	183.2459
PA3H6	0.000000	183.4449
PA3H7	0.000000	89.23400
PA3H8	0.000000	51.32700
PA3H9	0.000000	66.07000
PA3H10	0.000000	11.89200
PA3H11	0.000000	12.93000
PA3H12	666.5000	0.000000
PA3H13	0.000000	35.60000
PA3H14	0.000000	133.4400
PA3H15	0.000000	36.26000
PA3H16	0.000000	47.95000
PA3H17	0.000000	57.19000
PA3H18	0.000000	98.23000
PA3H19	0.000000	87.19000
PA3H20	0.000000	84.14090
PA3H21	0.000000	86.11880
PA3H22	0.000000	47.24000
PA3H23	0.000000	122.7000

PA3H24	0.000000	90.51000
PA3H25	0.000000	58.98000
PA4H1	0.000000	187.2410
PA4H2	0.000000	189.1400
PA4H3	0.000000	185.7820
PA4H4	0.000000	181.7220
PA4H5	0.000000	134.4859
PA4H6	0.000000	134.2849
PA4H7	0.000000	190.4740
PA4H8	0.000000	145.6870
PA4H9	0.000000	174.1100
PA4H10	0.000000	134.2520
PA4H11	0.000000	74.41000
PA4H12	0.000000	39.80000
PA4H13	0.000000	19.40000
PA4H14	0.000000	84.76000
PA4H15	0.000000	15.58000
PA4H16	0.000000	7.910000
PA4H17	0.000000	42.19000
PA4H18	0.000000	83.31000
PA4H19	0.000000	72.59000
PA4H20	0.000000	68.90090
PA4H21	0.000000	70.87880
PA4H22	316.5000	0.000000
PA4H23	0.000000	85.06000
PA4H24	0.000000	47.99000
PA4H25	0.000000	11.18000
PA6H1	0.000000	23.68100
PA6H2	0.000000	19.90000
PA6H3	0.000000	19.50200
PA6H4	0.000000	15.52200
PA6H5	0.000000	159.4059
PA6H6	0.000000	160.4049
PA6H7	0.000000	25.07400
PA6H8	0.000000	24.36700
PA6H9	0.000000	48.71000
PA6H10	0.000000	37.49200
PA6H11	0.000000	7.810000
PA6H12	1537.000	0.000000
PA6H13	0.000000	0.000000
PA6H14	0.000000	98.40000
PA6H15	0.000000	1.220000
PA6H16	0.000000	12.91000
PA6H17	0.000000	21.35000
PA6H18	0.000000	62.39000
PA6H19	0.000000	52.15000
PA6H20	0.000000	48.30090
PA6H21	0.000000	50.27880
PA6H22	0.000000	13.00000
PA6H23	0.000000	86.86000
PA6H24	0.000000	55.47000
PA6H25	0.000000	23.14000
PA8H1	0.000000	283.9710
PA8H2	0.000000	283.4700
PA8H3	0.000000	280.1120
PA8H4	0.000000	276.0520
PA8H5	0.000000	160.9759
PA8H6	0.000000	156.9349
PA8H7	0.000000	285.6040
PA8H8	0.000000	240.8170
PA8H9	0.000000	268.4400

PA8H10	0.000000	229.3820
PA8H11	0.000000	169.1400
PA8H12	0.000000	136.5300
PA8H13	0.000000	116.1300
PA8H14	0.000000	163.7300
PA8H15	0.000000	88.55000
PA8H16	0.000000	86.48000
PA8H17	0.000000	34.92000
PA8H18	0.000000	95.08000
PA8H19	0.000000	68.44000
PA8H20	0.000000	36.43090
PA8H21	0.000000	57.68880
PA8H22	0.000000	94.33000
PA8H23	0.000000	36.83000
PA8H24	171.0000	0.000000
PA8H25	0.000000	36.47000
PA9H1	0.000000	221.0510
PA9H2	0.000000	220.5500
PA9H3	0.000000	217.1920
PA9H4	0.000000	213.1320
PA9H5	0.000000	193.8159
PA9H6	0.000000	190.0149
PA9H7	0.000000	221.8840
PA9H8	0.000000	177.0970
PA9H9	0.000000	205.5200
PA9H10	0.000000	165.6620
PA9H11	0.000000	105.4200
PA9H12	0.000000	44.81000
PA9H13	0.000000	52.97000
PA9H14	0.000000	151.2100
PA9H15	0.000000	18.75000
PA9H16	0.000000	33.48000
PA9H17	155.0000	0.000000
PA9H18	0.000000	0.000000
PA9H19	0.000000	0.000000
PA9H20	0.000000	27.67090
PA9H21	0.000000	20.36880
PA9H22	0.000000	55.49000
PA9H23	0.000000	66.07000
PA9H24	0.000000	33.56000
PA9H25	0.000000	18.59000
PO4H1	0.000000	181.8808
PO4H2	0.000000	184.7497
PO4H3	0.000000	181.4938
PO4H4	0.000000	178.4548
PO4H5	0.000000	134.1286
PO4H6	0.000000	133.8765
PO4H7	0.000000	184.7564
PO4H8	0.000000	142.6750
PO4H9	0.000000	170.2302
PO4H10	0.000000	133.5373
PO4H11	0.000000	73.59320
PO4H12	0.000000	40.51470
PO4H13	0.000000	20.52310
PO4H14	0.000000	83.02430
PO4H15	0.000000	17.44843
PO4H16	0.000000	9.558915
PO4H17	0.000000	45.94218
PO4H18	0.000000	86.67930
PO4H19	0.000000	76.11756
PO4H20	0.000000	73.20952

PO4H21	0.000000	77.12222
PO4H22	1174275.	0.000000
PO4H23	0.000000	89.23589
PO4H24	0.000000	51.92596
PO4H25	0.000000	15.17211
PO7H1	0.000000	231.6986
PO7H2	0.000000	279.3675
PO7H3	0.000000	228.9116
PO7H4	0.000000	225.8726
PO7H5	0.000000	188.6664
PO7H6	0.000000	184.0143
PO7H7	0.000000	232.9742
PO7H8	0.000000	190.0929
PO7H9	0.000000	217.6480
PO7H10	0.000000	181.7551
PO7H11	0.000000	121.4110
PO7H12	0.000000	89.77253
PO7H13	0.000000	70.34092
PO7H14	0.000000	156.6821
PO7H15	0.000000	43.34625
PO7H16	0.000000	54.73674
PO7H17	939420.0	0.000000
PO7H18	0.000000	59.93713
PO7H19	0.000000	38.89538
PO7H20	0.000000	29.66735
PO7H21	0.000000	33.58004
PO7H22	0.000000	81.81782
PO7H23	0.000000	63.53372
PO7H24	0.000000	32.06378
PO7H25	0.000000	21.70994
PO8H1	0.000000	274.6748
PO8H2	0.000000	275.1437
PO8H3	0.000000	271.8878
PO8H4	0.000000	268.8488
PO8H5	0.000000	156.6826
PO8H6	0.000000	152.5905
PO8H7	0.000000	275.9504
PO8H8	0.000000	233.8691
PO8H9	0.000000	260.6242
PO8H10	0.000000	224.7313
PO8H11	0.000000	164.3872
PO8H12	0.000000	133.3087
PO8H13	0.000000	113.3171
PO8H14	0.000000	158.0583
PO8H15	0.000000	86.48248
PO8H16	0.000000	84.19296
PO8H17	0.000000	34.73622
PO8H18	0.000000	94.51335
PO8H19	0.000000	68.03160
PO8H20	0.000000	36.80357
PO8H21	0.000000	59.99626
PO8H22	0.000000	90.39405
PO8H23	0.000000	37.06994
PO8H24	352282.5	0.000000
PO8H25	0.000000	36.52616
PO10H1	0.000000	177.3661
PO10H2	0.000000	161.0350
PO10H3	0.000000	173.7791
PO10H4	0.000000	171.5401
PO10H5	0.000000	180.7339
PO10H6	0.000000	180.8818

PO10H7	0.000000	161.8417
PO10H8	0.000000	114.7203
PO10H9	0.000000	148.9955
PO10H10	0.000000	92.30260
PO10H11	0.000000	40.75850
PO10H12	1051475.	0.000000
PO10H13	0.000000	31.84840
PO10H14	0.000000	129.5496
PO10H15	0.000000	35.33373
PO10H16	0.000000	46.56422
PO10H17	0.000000	59.42748
PO10H18	0.000000	72.24460
PO10H19	0.000000	89.36285
PO10H20	0.000000	87.09482
PO10H21	0.000000	91.00751
PO10H22	0.000000	45.32530
PO10H23	0.000000	125.5212
PO10H24	0.000000	93.09126
PO10H25	0.000000	60.41741
PO11H1	0.000000	199.5218
PO11H2	0.000000	199.1908
PO11H3	0.000000	195.9349
PO11H4	0.000000	192.8959
PO11H5	0.000000	158.8896
PO11H6	0.000000	159.0376
PO11H7	0.000000	199.9975
PO11H8	0.000000	157.9161
PO11H9	0.000000	184.6713
PO11H10	0.000000	148.7784
PO11H11	0.000000	88.43428
PO11H12	0.000000	55.35578
PO11H13	0.000000	35.84418
PO11H14	0.000000	107.7054
PO11H15	0.000000	8.449515
PO11H16	469710.0	0.000000
PO11H17	0.000000	33.02326
PO11H18	0.000000	67.44039
PO11H19	0.000000	63.19864
PO11H20	0.000000	60.53060
PO11H21	0.000000	64.36330
PO11H22	0.000000	23.96109
PO11H23	0.000000	98.87698
PO11H24	0.000000	61.80704
PO11H25	0.000000	25.05319
PO12H1	0.000000	232.0186
PO12H2	0.000000	232.4875
PO12H3	0.000000	229.2316
PO12H4	0.000000	226.1926
PO12H5	0.000000	184.1864
PO12H6	0.000000	179.5343
PO12H7	0.000000	233.2942
PO12H8	0.000000	191.2129
PO12H9	0.000000	217.9680
PO12H10	0.000000	182.0751
PO12H11	0.000000	121.7310
PO12H12	0.000000	89.85253
PO12H13	0.000000	70.74093
PO12H14	0.000000	165.8021
PO12H15	0.000000	43.74625
PO12H16	0.000000	55.13674
PO12H17	704565.0	0.000000

PO12H18	0.000000	63.05713
PO12H19	0.000000	36.65538
PO12H20	0.000000	16.54734
PO12H21	0.000000	20.46004
PO12H22	0.000000	82.21783
PO12H23	0.000000	50.49372
PO12H24	0.000000	27.66378
PO12H25	0.000000	21.70993
PD1H1	0.000000	62.99100
PD1H2	0.000000	44.18000
PD1H3	0.000000	75.52200
PD1H4	0.000000	71.42200
PD1H5	0.000000	161.6559
PD1H6	0.000000	161.1049
PD1H7	0.000000	47.37400
PD1H8	0.000000	18.17700
PD1H9	0.000000	22.41000
PD1H10	0.000000	6.972000
PD1H11	0.000000	7.470000
PD1H12	2769.300	0.000000
PD1H13	0.000000	12.32000
PD1H14	0.000000	113.2000
PD1H15	0.000000	12.49000
PD1H16	0.000000	24.39500
PD1H17	0.000000	31.57500
PD1H18	0.000000	72.99000
PD1H19	0.000000	61.79500
PD1H20	0.000000	57.98090
PD1H21	0.000000	58.06380
PD1H22	0.000000	26.10000
PD1H23	0.000000	96.67000
PD1H24	0.000000	64.71500
PD1H25	0.000000	32.33000
PD2H1	0.000000	215.4760
PD2H2	0.000000	219.6250
PD2H3	0.000000	195.3670
PD2H4	0.000000	211.1070
PD2H5	0.000000	20.94090
PD2H6	0.000000	21.18990
PD2H7	0.000000	218.2590
PD2H8	0.000000	170.8220
PD2H9	0.000000	200.0950
PD2H10	0.000000	157.1370
PD2H11	0.000000	97.79500
PD2H12	0.000000	61.28500
PD2H13	0.000000	41.28500
PD2H14	0.000000	43.92500
PD2H15	0.000000	35.77500
PD2H16	0.000000	28.48000
PD2H17	0.000000	34.86000
PD2H18	0.000000	95.47500
PD2H19	0.000000	69.08000
PD2H20	0.000000	35.66590
PD2H21	0.000000	29.34880
PD2H22	0.000000	23.86500
PD2H23	0.000000	27.95500
PD2H24	2606.100	0.000000
PD2H25	0.000000	35.61500
PD3H1	0.000000	111.3110
PD3H2	0.000000	92.34000
PD3H3	0.000000	123.7620

PD3H4	0.000000	123.6620
PD3H5	0.000000	184.2959
PD3H6	0.000000	184.5449
PD3H7	0.000000	95.53400
PD3H8	0.000000	54.97700
PD3H9	0.000000	70.57000
PD3H10	0.000000	13.29200
PD3H11	0.000000	14.43000
PD3H12	1601.400	0.000000
PD3H13	0.000000	35.20000
PD3H14	0.000000	135.8400
PD3H15	0.000000	35.13000
PD3H16	0.000000	47.03500
PD3H17	0.000000	54.21500
PD3H18	0.000000	95.63000
PD3H19	0.000000	84.43500
PD3H20	0.000000	80.62090
PD3H21	0.000000	80.70380
PD3H22	0.000000	47.94000
PD3H23	0.000000	119.3100
PD3H24	0.000000	87.35500
PD3H25	0.000000	55.77000
PD4H1	0.000000	192.4910
PD4H2	0.000000	193.4400
PD4H3	0.000000	189.9820
PD4H4	0.000000	184.9220
PD4H5	0.000000	134.8359
PD4H6	0.000000	134.6849
PD4H7	0.000000	196.0740
PD4H8	0.000000	148.6370
PD4H9	0.000000	177.9100
PD4H10	0.000000	134.9520
PD4H11	0.000000	75.21000
PD4H12	0.000000	39.10000
PD4H13	0.000000	18.30000
PD4H14	0.000000	86.46000
PD4H15	0.000000	13.75000
PD4H16	0.000000	6.295000
PD4H17	0.000000	38.51500
PD4H18	0.000000	80.01000
PD4H19	0.000000	69.13500
PD4H20	0.000000	64.68090
PD4H21	0.000000	64.76380
PD4H22	377.4000	0.000000
PD4H23	0.000000	80.97000
PD4H24	0.000000	44.13500
PD4H25	0.000000	7.270000
PD10H1	0.000000	189.3910
PD10H2	0.000000	171.1400
PD10H3	0.000000	183.6820
PD10H4	0.000000	179.4220
PD10H5	0.000000	182.8559
PD10H6	0.000000	183.1049
PD10H7	0.000000	174.5740
PD10H8	0.000000	122.0970
PD10H9	0.000000	158.0900
PD10H10	0.000000	95.13200
PD10H11	0.000000	43.79000
PD10H12	351.9000	0.000000
PD10H13	0.000000	31.04000
PD10H14	0.000000	134.4000

PD10H15	0.000000	33.05000
PD10H16	0.000000	44.71500
PD10H17	0.000000	53.41500
PD10H18	0.000000	66.99000
PD10H19	0.000000	83.79500
PD10H20	0.000000	79.98090
PD10H21	0.000000	80.06380
PD10H22	0.000000	46.74000
PD10H23	0.000000	118.6700
PD10H24	0.000000	86.71500
PD10H25	0.000000	53.93000
SCH1	0.000000	0.000000
SCH2	0.000000	0.000000
SCH3	0.000000	0.000000
SCH4	0.000000	0.000000
SCH5	0.000000	0.000000
SCH6	0.000000	0.000000
SCH7	0.000000	0.000000
SCH8	0.000000	0.000000
SCH9	0.000000	0.000000
SCH10	0.000000	0.000000
SCH11	0.000000	0.000000
SCH12	5376.221	0.000000
SCH13	0.000000	0.000000
SCH14	0.000000	0.000000
SCH15	0.000000	0.000000
SCH16	0.000000	0.000000
SCH17	708.7510	0.000000
SCH18	0.000000	0.000000
SCH19	0.000000	0.000000
SCH20	0.000000	0.000000
SCH21	0.000000	0.000000
SCH22	53.11500	0.000000
SCH23	0.000000	0.000000
SCH24	105.0670	0.000000
SCH25	0.000000	0.000000
PAH1	0.000000	0.000000
PAH2	0.000000	0.000000
PAH3	0.000000	0.000000
PAH4	0.000000	0.000000
PAH5	0.000000	0.000000
PAH6	0.000000	0.000000
PAH7	0.000000	0.000000
PAH8	0.000000	0.000000
PAH9	0.000000	0.000000
PAH10	0.000000	0.000000
PAH11	0.000000	0.000000
PAH12	2758.500	0.000000
PAH13	0.000000	0.000000
PAH14	0.000000	0.000000
PAH15	0.000000	0.000000
PAH16	0.000000	0.000000
PAH17	155.0000	0.000000
PAH18	0.000000	0.000000
PAH19	0.000000	0.000000
PAH20	0.000000	0.000000
PAH21	0.000000	0.000000
PAH22	316.5000	0.000000
PAH23	0.000000	0.000000
PAH24	171.0000	0.000000
PAH25	0.000000	0.000000

POH1	0.000000	0.000000
POH2	0.000000	0.000000
POH3	0.000000	0.000000
POH4	0.000000	0.000000
POH5	0.000000	0.000000
POH6	0.000000	0.000000
POH7	0.000000	0.000000
POH8	0.000000	0.000000
POH9	0.000000	0.000000
POH10	0.000000	0.000000
POH11	0.000000	0.000000
POH12	1051475.	0.000000
POH13	0.000000	0.000000
POH14	0.000000	0.000000
POH15	0.000000	0.000000
POH16	469710.0	0.000000
POH17	1643985.	0.000000
POH18	0.000000	0.000000
POH19	0.000000	0.000000
POH20	0.000000	0.000000
POH21	0.000000	0.000000
POH22	1174275.	0.000000
POH23	0.000000	0.000000
POH24	352282.5	0.000000
POH25	0.000000	0.000000
PDH1	0.000000	0.000000
PDH2	0.000000	0.000000
PDH3	0.000000	0.000000
PDH4	0.000000	0.000000
PDH5	0.000000	0.000000
PDH6	0.000000	0.000000
PDH7	0.000000	0.000000
PDH8	0.000000	0.000000
PDH9	0.000000	0.000000
PDH10	0.000000	0.000000
PDH11	0.000000	0.000000
PDH12	4722.600	0.000000
PDH13	0.000000	0.000000
PDH14	0.000000	0.000000
PDH15	0.000000	0.000000
PDH16	0.000000	0.000000
PDH17	0.000000	0.000000
PDH18	0.000000	0.000000
PDH19	0.000000	0.000000
PDH20	0.000000	0.000000
PDH21	0.000000	0.000000
PDH22	377.4000	0.000000
PDH23	0.000000	0.000000
PDH24	2606.100	0.000000
PDH25	0.000000	0.000000
M	0.1000000E+09	0.000000
B1	0.000000	-0.4371164E+10
B2	0.000000	-0.5291064E+10
B3	0.000000	-0.5255264E+10
B4	0.000000	-0.6489264E+10
B5	0.000000	-0.6427654E+10
B6	0.000000	-0.6097554E+10
B7	0.000000	-0.4644464E+10
B8	0.000000	-0.3835764E+10
B9	0.000000	-0.5928064E+10
B10	0.000000	-0.4442264E+10

B11	0.000000	-0.1558064E+10
B12	1.000000	2936491.
B13	0.000000	-0.8370635E+09
B14	0.000000	2936491.
B15	0.000000	2936491.
B16	1.000000	2936491.
B17	1.000000	2936491.
B18	0.000000	-0.2756064E+10
B19	0.000000	-0.1585064E+10
B20	0.000000	-0.1099154E+10
B21	0.000000	-0.1153944E+10
B22	1.000000	2936491.
B23	0.000000	2936491.
B24	1.000000	2936491.
B25	0.000000	2936491.
D1H1	58.50000	0.000000
D1H2	31.80000	0.000000
D1H3	72.30000	0.000000
D1H4	60.50000	0.000000
D1H5	199.0000	0.000000
D1H6	202.0000	0.000000
D1H7	32.50000	0.000000
D1H8	29.30000	0.000000
D1H9	1.000000	0.000000
D1H10	27.40000	0.000000
D1H11	63.20000	0.000000
D1H12	86.50000	0.000000
D1H13	94.90000	0.000000
D1H14	207.0000	0.000000
D1H15	112.0000	0.000000
D1H16	125.0000	0.000000
D1H17	152.0000	0.000000
D1H18	166.0000	0.000000
D1H19	168.0000	0.000000
D1H20	176.0000	0.000000
D1H21	192.0000	0.000000
D1H22	113.0000	0.000000
D1H23	237.0000	0.000000
D1H24	195.0000	0.000000
D1H25	155.0000	0.000000
D2H1	227.0000	0.000000
D2H2	229.0000	0.000000
D2H3	200.0000	0.000000
D2H4	213.0000	0.000000
D2H5	1.000000	0.000000
D2H6	5.000000	0.000000
D2H7	224.0000	0.000000
D2H8	198.0000	0.000000
D2H9	201.0000	0.000000
D2H10	193.0000	0.000000
D2H11	154.0000	0.000000
D2H12	141.0000	0.000000
D2H13	109.0000	0.000000
D2H14	98.30000	0.000000
D2H15	119.0000	0.000000
D2H16	108.0000	0.000000
D2H17	134.0000	0.000000
D2H18	172.0000	0.000000
D2H19	155.0000	0.000000
D2H20	126.0000	0.000000
D2H21	134.0000	0.000000

D2H22	88.10000	0.000000
D2H23	129.0000	0.000000
D2H24	92.00000	0.000000
D2H25	137.0000	0.000000
D3H1	84.60000	0.000000
D3H2	57.70000	0.000000
D3H3	98.30000	0.000000
D3H4	91.50000	0.000000
D3H5	193.0000	0.000000
D3H6	197.0000	0.000000
D3H7	58.40000	0.000000
D3H8	41.00000	0.000000
D3H9	26.90000	0.000000
D3H10	1.000000	0.000000
D3H11	37.60000	0.000000
D3H12	52.20000	0.000000
D3H13	89.20000	0.000000
D3H14	201.0000	0.000000
D3H15	106.0000	0.000000
D3H16	119.0000	0.000000
D3H17	146.0000	0.000000
D3H18	160.0000	0.000000
D3H19	162.0000	0.000000
D3H20	170.0000	0.000000
D3H21	186.0000	0.000000
D3H22	106.0000	0.000000
D3H23	231.0000	0.000000
D3H24	189.0000	0.000000
D3H25	150.0000	0.000000
D4H1	141.0000	0.000000
D4H2	139.0000	0.000000
D4H3	136.0000	0.000000
D4H4	123.0000	0.000000
D4H5	86.10000	0.000000
D4H6	89.60000	0.000000
D4H7	139.0000	0.000000
D4H8	113.0000	0.000000
D4H9	116.0000	0.000000
D4H10	108.0000	0.000000
D4H11	68.50000	0.000000
D4H12	56.00000	0.000000
D4H13	23.00000	0.000000
D4H14	94.20000	0.000000
D4H15	34.20000	0.000000
D4H16	23.00000	0.000000
D4H17	81.30000	0.000000
D4H18	95.40000	0.000000
D4H19	97.80000	0.000000
D4H20	105.0000	0.000000
D4H21	121.0000	0.000000
D4H22	1.000000	0.000000
D4H23	138.0000	0.000000
D4H24	89.90000	0.000000
D4H25	44.30000	0.000000
D5H1	204.0000	0.000000
D5H2	199.0000	0.000000
D5H3	196.0000	0.000000
D5H4	183.0000	0.000000
D5H5	129.0000	0.000000
D5H6	127.0000	0.000000
D5H7	200.0000	0.000000

D5H8	174.0000	0.000000
D5H9	176.0000	0.000000
D5H10	169.0000	0.000000
D5H11	129.0000	0.000000
D5H12	118.0000	0.000000
D5H13	86.10000	0.000000
D5H14	198.0000	0.000000
D5H15	67.40000	0.000000
D5H16	80.30000	0.000000
D5H17	30.10000	0.000000
D5H18	48.40000	0.000000
D5H19	31.00000	0.000000
D5H20	17.70000	0.000000
D5H21	21.80000	0.000000
D5H22	104.0000	0.000000
D5H23	73.90000	0.000000
D5H24	39.70000	0.000000
D5H25	62.80000	0.000000
D6H1	30.30000	0.000000
D6H2	21.20000	0.000000
D6H3	21.90000	0.000000
D6H4	9.000000	0.000000
D6H5	211.0000	0.000000
D6H6	216.0000	0.000000
D6H7	26.00000	0.000000
D6H8	55.10000	0.000000
D6H9	53.00000	0.000000
D6H10	80.80000	0.000000
D6H11	79.00000	0.000000
D6H12	100.0000	0.000000
D6H13	92.50000	0.000000
D6H14	205.0000	0.000000
D6H15	110.0000	0.000000
D6H16	123.0000	0.000000
D6H17	149.0000	0.000000
D6H18	163.0000	0.000000
D6H19	166.0000	0.000000
D6H20	173.0000	0.000000
D6H21	189.0000	0.000000
D6H22	111.0000	0.000000
D6H23	234.0000	0.000000
D6H24	193.0000	0.000000
D6H25	153.0000	0.000000
D7H1	181.0000	0.000000
D7H2	235.0000	0.000000
D7H3	173.0000	0.000000
D7H4	160.0000	0.000000
D7H5	132.0000	0.000000
D7H6	130.0000	0.000000
D7H7	177.0000	0.000000
D7H8	150.0000	0.000000
D7H9	153.0000	0.000000
D7H10	146.0000	0.000000
D7H11	106.0000	0.000000
D7H12	95.30000	0.000000
D7H13	63.00000	0.000000
D7H14	164.0000	0.000000
D7H15	44.30000	0.000000
D7H16	57.20000	0.000000
D7H17	1.600000	0.000000
D7H18	39.70000	0.000000

D7H19	29.00000	0.000000
D7H20	28.30000	0.000000
D7H21	44.30000	0.000000
D7H22	81.00000	0.000000
D7H23	83.60000	0.000000
D7H24	42.80000	0.000000
D7H25	30.20000	0.000000
D8H1	233.0000	0.000000
D8H2	228.0000	0.000000
D8H3	225.0000	0.000000
D8H4	212.0000	0.000000
D8H5	90.30000	0.000000
D8H6	89.00000	0.000000
D8H7	229.0000	0.000000
D8H8	203.0000	0.000000
D8H9	205.0000	0.000000
D8H10	198.0000	0.000000
D8H11	158.0000	0.000000
D8H12	148.0000	0.000000
D8H13	115.0000	0.000000
D8H14	164.0000	0.000000
D8H15	96.50000	0.000000
D8H16	92.30000	0.000000
D8H17	43.30000	0.000000
D8H18	81.20000	0.000000
D8H19	63.70000	0.000000
D8H20	35.50000	0.000000
D8H21	75.60000	0.000000
D8H22	90.00000	0.000000
D8H23	48.80000	0.000000
D8H24	1.000000	0.000000
D8H25	47.00000	0.000000
D9H1	193.0000	0.000000
D9H2	188.0000	0.000000
D9H3	185.0000	0.000000
D9H4	172.0000	0.000000
D9H5	170.0000	0.000000
D9H6	169.0000	0.000000
D9H7	188.0000	0.000000
D9H8	162.0000	0.000000
D9H9	165.0000	0.000000
D9H10	157.0000	0.000000
D9H11	117.0000	0.000000
D9H12	72.00000	0.000000
D9H13	74.70000	0.000000
D9H14	187.0000	0.000000
D9H15	47.90000	0.000000
D9H16	64.70000	0.000000
D9H17	38.30000	0.000000
D9H18	1.000000	0.000000
D9H19	16.80000	0.000000
D9H20	63.20000	0.000000
D9H21	67.60000	0.000000
D9H22	80.10000	0.000000
D9H23	124.0000	0.000000
D9H24	81.60000	0.000000
D9H25	63.30000	0.000000
D10H1	131.0000	0.000000
D10H2	105.0000	0.000000
D10H3	122.0000	0.000000
D10H4	110.0000	0.000000

D10H5	140.0000	0.000000
D10H6	144.0000	0.000000
D10H7	106.0000	0.000000
D10H8	73.70000	0.000000
D10H9	85.10000	0.000000
D10H10	52.10000	0.000000
D10H11	23.10000	0.000000
D10H12	1.000000	0.000000
D10H13	32.80000	0.000000
D10H14	148.0000	0.000000
D10H15	52.20000	0.000000
D10H16	64.90000	0.000000
D10H17	93.80000	0.000000
D10H18	73.00000	0.000000
D10H19	110.0000	0.000000
D10H20	118.0000	0.000000
D10H21	134.0000	0.000000
D10H22	53.30000	0.000000
D10H23	179.0000	0.000000
D10H24	137.0000	0.000000
D10H25	96.50000	0.000000
D11H1	153.0000	0.000000
D11H2	147.0000	0.000000
D11H3	144.0000	0.000000
D11H4	131.0000	0.000000
D11H5	107.0000	0.000000
D11H6	111.0000	0.000000
D11H7	148.0000	0.000000
D11H8	122.0000	0.000000
D11H9	124.0000	0.000000
D11H10	117.0000	0.000000
D11H11	77.00000	0.000000
D11H12	64.50000	0.000000
D11H13	32.10000	0.000000
D11H14	115.0000	0.000000
D11H15	12.90000	0.000000
D11H16	1.000000	0.000000
D11H17	55.10000	0.000000
D11H18	61.30000	0.000000
D11H19	71.60000	0.000000
D11H20	79.10000	0.000000
D11H21	95.00000	0.000000
D11H22	20.90000	0.000000
D11H23	140.0000	0.000000
D11H24	92.20000	0.000000
D11H25	46.60000	0.000000
D12H1	190.0000	0.000000
D12H2	185.0000	0.000000
D12H3	182.0000	0.000000
D12H4	169.0000	0.000000
D12H5	135.0000	0.000000
D12H6	133.0000	0.000000
D12H7	186.0000	0.000000
D12H8	160.0000	0.000000
D12H9	162.0000	0.000000
D12H10	155.0000	0.000000
D12H11	115.0000	0.000000
D12H12	104.0000	0.000000
D12H13	72.10000	0.000000
D12H14	184.0000	0.000000
D12H15	53.40000	0.000000

D12H16	66.30000	0.000000
D12H17	10.20000	0.000000
D12H18	52.20000	0.000000
D12H19	34.80000	0.000000
D12H20	20.50000	0.000000
D12H21	36.50000	0.000000
D12H22	90.10000	0.000000
D12H23	75.90000	0.000000
D12H24	45.90000	0.000000
D12H25	38.80000	0.000000
DH1P	235.0000	0.000000
DH2P	216.0000	0.000000
DH3P	214.0000	0.000000
DH4P	194.0000	0.000000
DH5P	137.0000	0.000000
DH6P	138.0000	0.000000
DH7P	242.0000	0.000000
DH8P	189.0000	0.000000
DH9P	206.0000	0.000000
DH10P	144.0000	0.000000
DH11P	146.0000	0.000000
DH12P	116.0000	0.000000
DH13P	108.0000	0.000000
DH14P	164.0000	0.000000
DH15P	93.40000	0.000000
DH16P	97.70000	0.000000
DH17P	56.50000	0.000000
DH18P	64.00000	0.000000
DH19P	60.90000	0.000000
DH20P	45.60000	0.000000
DH21P	7.700000	0.000000
DH22P	130.0000	0.000000
DH23P	48.20000	0.000000
DH24P	52.90000	0.000000
DH25P	51.80000	0.000000
CGP	0.9394067E+09	0.000000
CTR	0.1183196E+09	0.000000
CLAND	0.2500000E+08	0.000000
LT	20.00000	0.000000
I	0.1000000	0.000000
CRT	0.1174596	0.000000
CINV	0.1468245E+08	0.000000

A.1.4 Area fragmentation (Pareto analysis)

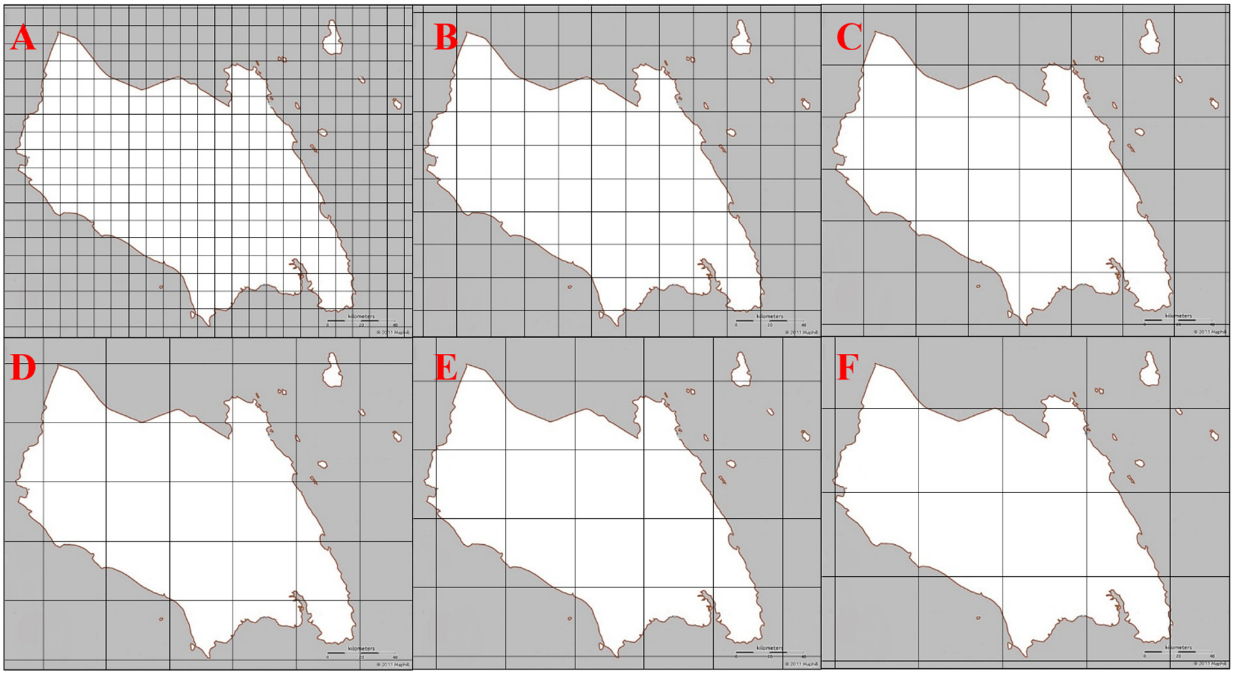

Figure A.2: Area Fragmentation (A: 100 km^2; B: 300 km^2; C: 900 km^2; D: 1200 km^2: E: 1600 km^2; F: 2500 km^2) (Maphill, 2013).

A.2 Appendix for Chapter 5

A.2.1 Lingo code for detail transportation design

```
!Objective function;
min=C_Tr;

!Delivered capacity;
F=10;![t/d];
F=FM1+FM2+FM3+FM4;

!Capacity constraint;
CapM1=5;CapM2=10;CapM3=20;CapM4=32; ![t/vehicle];

!Travelling distance;
Dij=5;![km];

!Speed=Sp, leadtime-DT;
SpM1=60;SPM2=60;SPM3=60;SPM4=60;
DTM1=0.33;DTM2=0.67;DTM3=1;DTM4=1.33;

!Maximum trip per day;
Trip_max_M1=@rounddown(20/((2*Dij)/SpM1+DTM1),0);
Trip_max_M2=@rounddown(20/((2*Dij)/SpM2+DTM2),0);
Trip_max_M3=@rounddown(20/((2*Dij)/SpM3+DTM3),0);
Trip_max_M4=@rounddown(20/((2*Dij)/SpM4+DTM4),0);
```

```
!Trip required;
Trip_req_M1=@roundup(F/CapM1,0); Trip_req_M2=@roundup(F/CapM2,0);
Trip_req_M3=@roundup(F/CapM3,0); Trip_req_M4=@roundup(F/CapM4,0);

!number of vehicle required;
n_M1=@roundup(Trip_req_M1/Trip_max_M1,0);
n_M2=@roundup(Trip_req_M2/Trip_max_M2,0);
n_M3=@roundup(Trip_req_M3/Trip_max_M3,0);
n_M4=@roundup(Trip_req_M4/Trip_max_M4,0);

!Big M determination;
M=100000;
FM1<=M*B1;FM2<=M*B2;FM3<=M*B3;FM4<=M*B4;
@bin(B1);@bin(B2);@bin(B3);@bin(B4);
B1+B2+B3+B4=1;

!Transportation data;
C_Tr=C_OPEX+C_CAPEX+C_CO2;
LS=10;![y];  OPD=355;![d/y]; HW=20;![RM/h]; C_Fuel=1.90;![RM/L];

!Procurement cost;
C_M1=70000; C_M2=90000; C_M3=125000; C_M4=150000;![RM];C_plant=0.3;

!Fuel consumption rate;
Fuel_consM1=0.213; Fuel_consM2=0.213; Fuel_consM3=0.235;
Fuel_consM4=0.235; ![L/km];

!Maintenance cost;
C_MainM1=0.18; C_MainM2=0.22; C_MainM3=0.34; C_MainM4=0.45; ![RM/km];

!Emission;
fCO2M1=0.5538; fCO2M2=0.5538; fCO2M3=0.611; fCO2M4=0.611;![kg/km];

!Transportation cost calculation;
C_CAPEX=(B1*n_M1*C_M1+B2*n_M2*C_M2+B3*n_M3*C_M3+B4*n_M4*C_M4)/LS;
C_OPEX=C_Labour+C_Mile+C_Maintain;
C_Labour=OPD*HW*(B1*Trip_req_M1*((2*Dij)/SpM1+DTM1)+B2*Trip_req_M2*((
2*Dij)/SpM2+DTM2)+B3*Trip_req_M3*((2*Dij)/SpM3+DTM3)+B4*Trip_req_M4*(
(2*Dij)/SpM4+DTM4));
C_Mile=2*C_Fuel*OPD*(B1*Trip_req_M1*Dij*Fuel_consM1+B2*Trip_req_M2*Di
j*Fuel_consM2+B3*Trip_req_M3*Dij*Fuel_consM3+B4*Trip_req_M4*Dij*Fuel_
consM4);
C_Maintain=2*OPD*(B1*Trip_req_M1*Dij*C_MainM1+B2*Trip_req_M2*Dij*C_Ma
inM2+B3*Trip_req_M3*Dij*C_MainM3+B4*Trip_req_M4*Dij*C_MainM4);

!Carbon Penalty;
C_CO2=2*(1-.25)*OPD*Dij*C_plant*(B1*Trip_req_M1*fCO2M1+B2*Trip_req_M2
*fCO2M2+B3*Trip_req_M3*fCO2M3+B4*Trip_req_M4*fCO2M4)/1.12;
End
```

A.2.2 Sample solution

```
Global optimal solution found.
  Objective value:                              17552.97
  Objective bound:                              17552.97
  Infeasibilities:                              0.000000
  Extended solver steps:                               0
  Total solver iterations:                             0
  Elapsed runtime seconds:                          0.25
```

```
Model Class:                                          MILP

Total variables:                   15
Nonlinear variables:                0
Integer variables:                  4

Total constraints:                 14
Nonlinear constraints:              0

Total nonzeros:                    50
Nonlinear nonzeros:                 0
```

Variable	Value	Reduced Cost
C_TR	17552.97	0.000000
F	10.00000	0.000000
FM1	0.000000	0.000000
FM2	10.00000	0.000000
FM3	0.000000	0.000000
FM4	0.000000	0.000000
CAPM1	5.000000	0.000000
CAPM2	10.00000	0.000000
CAPM3	20.00000	0.000000
CAPM4	32.00000	0.000000
DIJ	5.000000	0.000000
SPM1	60.00000	0.000000
SPM2	60.00000	0.000000
SPM3	60.00000	0.000000
SPM4	60.00000	0.000000
DTM1	0.3300000	0.000000
DTM2	0.6700000	0.000000
DTM3	1.000000	0.000000
DTM4	1.330000	0.000000
TRIP_MAX_M1	40.00000	0.000000
TRIP_MAX_M2	23.00000	0.000000
TRIP_MAX_M3	17.00000	0.000000
TRIP_MAX_M4	13.00000	0.000000
TRIP_REQ_M1	2.000000	0.000000
TRIP_REQ_M2	1.000000	0.000000
TRIP_REQ_M3	1.000000	0.000000
TRIP_REQ_M4	1.000000	0.000000
N_M1	1.000000	0.000000
N_M2	1.000000	0.000000
N_M3	1.000000	0.000000
N_M4	1.000000	0.000000
M	100000.0	0.000000
B1	0.000000	18993.94
B2	1.000000	17552.97
B3	0.000000	24011.15
B4	0.000000	29244.65
C_OPEX	8158.018	0.000000
C_CAPEX	9000.000	0.000000
C_CO2	394.9533	0.000000
LS	10.00000	0.000000
OPD	355.0000	0.000000
HW	20.00000	0.000000
C_FUEL	1.900000	0.000000
C_M1	70000.00	0.000000
C_M2	90000.00	0.000000
C_M3	125000.0	0.000000
C_M4	150000.0	0.000000
C_PLANT	0.3000000	0.000000

```
  FUEL_CONSM1        0.2130000           0.000000
  FUEL_CONSM2        0.2130000           0.000000
  FUEL_CONSM3        0.2350000           0.000000
  FUEL_CONSM4        0.2350000           0.000000
     C_MAINM1        0.1800000           0.000000
     C_MAINM2        0.2200000           0.000000
     C_MAINM3        0.3400000           0.000000
     C_MAINM4        0.4500000           0.000000
       FCO2M1        0.5538000           0.000000
       FCO2M2        0.5538000           0.000000
       FCO2M3        0.6110000           0.000000
       FCO2M4        0.6110000           0.000000
     C_LABOUR         5940.333           0.000000
       C_MILE         1436.685           0.000000
   C_MAINTAIN         781.0000           0.000000
```

A.3 Appendix for Chapter 6

A.3.1 Lingo code for transportation design

```
!max=lamda_macro;!max=C_Tr;
min=GWP;!min=AP;!min=POCP;!min=NP;!max=ATP;!min=C_Tr;!max=GWP;
@free(C_Tr);@free(GWP); @free(AP);  @free(POCP); @free(NP);
@free(ATP);

!Input data;
F=0.437;![t/d];
D1=38.3;![km];

!Flow balance between vehicles;
F=F1M1+F1M2+F1M3+F1M4;

!Vehicle data, Cap=capacity constraint, Sp=speed, DT=delay time;
CapM1=5;CapM2=10;CapM3=15.12;CapM4=30.4; ![t/vehicle];
SpM1=60;SPM2=60;SPM3=60;SPM4=60;
DTM1=0.33;DTM2=0.67;DTM3=1;DTM4=1.33;

!Maximum trip per day;
Trip_max_D1M1=@rounddown(20/((2*D1)/SpM1+DTM1),0);
Trip_max_D1M2=@rounddown(20/((2*D1)/SpM2+DTM2),0);
Trip_max_D1M3=@rounddown(20/((2*D1)/SpM3+DTM3),0);
Trip_max_D1M4=@rounddown(20/((2*D1)/SpM4+DTM4),0);

!number of trip required;
Trip_req_M1=@roundup(F/CapM1,0); Trip_req_M2=@roundup(F/CapM2,0);
Trip_req_M3=@roundup(F/CapM3,0); Trip_req_M4=@roundup(F/CapM4,0);

!number of vehicle required;
n_D1M1=@roundup(Trip_req_M1/Trip_max_D1M1,0);
n_D1M2=@roundup(Trip_req_M2/Trip_max_D1M2,0);
n_D1M3=@roundup(Trip_req_M3/Trip_max_D1M3,0);
n_D1M4=@roundup(Trip_req_M4/Trip_max_D1M4,0);

!Big M determination;
M=100000;
F1M1<M*B11;  F1M2<M*B12;  F1M3<M*B13;  F1M4<M*B14;
B11+B12+B13+B14=1;
@bin(B11);@bin(B12);@bin(B13);@bin(B14);
```

```
!Economic Performance;
LS=10;![y];  OPD=355;![d/y]; HW=20;![RM/h]; C_Fuel=1.90;![RM/L];

!Procurement cost;
C_M1=70000; C_M2=90000; C_M3=125000; C_M4=150000;![RM];

!Fuel consumption rate;
Fuel_consM1=0.213; Fuel_consM2=0.213; Fuel_consM3=0.235;
Fuel_consM4=0.235; ![L/km];

!Maintenance cost;
C_MainM1=0.18; C_MainM2=0.22; C_MainM3=0.34; C_MainM4=0.45; ![RM/km];

!Cost calculation;
C_Tr=C_OPEXD1+C_CAPEXD1;
C_CAPEXD1=(B11*n_D1M1*C_M1+B12*n_D1M2*C_M2+B13*n_D1M3*C_M3+B14*n_D1M4
*C_M4)/LS;
C_OPEXD1=C_LabourD1+C_MileD1+C_MaintainD1;
C_LabourD1=OPD*HW*(B11*Trip_req_M1*((2*D1)/SpM1+DTM1)+B12*Trip_req_M2
*((2*D1)/SpM2+DTM2)+B13*Trip_req_M3*((2*D1)/SpM3+DTM3)+B14*Trip_req_M
4*((2*D1)/SpM4+DTM4));
C_MileD1=2*C_Fuel*OPD*(B11*Trip_req_M1*D1*Fuel_consM1+B12*Trip_req_M2
*D1*Fuel_consM2+B13*Trip_req_M3*D1*Fuel_consM3+B14*Trip_req_M4*D1*Fue
l_consM4);
C_MaintainD1=2*OPD*(B11*Trip_req_M1*D1*C_MainM1+B12*Trip_req_M2*D1*C_
MainM2+B13*Trip_req_M3*D1*C_MainM3+B14*Trip_req_M4*D1*C_MainM4);

!Environmental Performance;
XCO2=2.6; XCH4=0.00056; XCO=0.2768; XN2O=0.000028;![kg/L];
XR134A=0.088; ![kg/vehicle/y];
XNOx=0.004408; XSO2=0.000017; XHC=0.006851;
FCO2D1=2*D1*OPD*XCO2*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fue
l_consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FCH4D1=2*D1*OPD*XCH4*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fue
l_consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FCOD1=2*D1*OPD*XCO*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fuel_
consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FN2OD1=2*D1*OPD*XN2O*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fue
l_consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FNOxD1=2*D1*OPD*XNOx*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fue
l_consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FSO2D1=2*D1*OPD*XSO2*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fue
l_consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FHCD1=2*D1*OPD*XHC*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fuel_
consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FR134AD1=XR134A*(B11*n_D1M1+B12*n_D1M2+B13*n_D1M3+B14*n_D1M4);

!PEI (WAR)GWP:global warming potential, POCP:photochemical ozone
creation potential, NP:neutrification potential, ATP:Aquatic toxicity
potential;
GWP_CO2=1;   AP_CO2=0;   POCP_CO2=0;       NP_CO2=0;     ATP_CO2=0;
GWP_CO=0;    AP_CO=0;    POCP_CO=0.01470;  NP_CO=0;      ATP_CO=0;
GWP_CH4=23;  AP_CH4=0;   POCP_CH4=0.00384; NP_CH4=0;     ATP_CH4=0;
GWP_NOx=0;   AP_NOX=1.1; POCP_NOx=1.3;     NP_NOx=0.13;  ATP_NOx=0;
GWP_N2O=296; AP_N2O=0.7; POCP_N2O=0.00384; NP_N2O=0;     ATP_N2O=0;
GWP_SO2=0;   AP_SO2=1;   POCP_SO2=0.125;   NP_SO2=0;     ATP_SO2=0;
GWP_HC=0;    AP_HC=0.018;POCP_HC=0.416;    NP_HC=0;      ATP_HC=0;
GWP_R=1320;  AP_R=0;     POCP_R=0.0025;    NP_R=0;  ATP_R=0.00205338;

GWP=FCO2D1*GWP_CO2  +FCOD1*GWP_CO +FCH4D1*GWP_CH4 +FN2OD1*GWP_N2O
```

```
+FNOxD1*GWP_NOx +FSO2D1*GWP_SO2 +FHCD1*GWP_HC +FR134AD1*GWP_R;
AP=FCO2D1*AP_CO2    +FCOD1*AP_CO  +FCH4D1*AP_CH4  +FN2OD1*AP_N2O
+FNOxD1*AP_NOx  +FSO2D1*AP_SO2  +FHCD1*AP_HC  +FR134AD1*AP_R;
POCP=FCO2D1*POCP_CO2+FCOD1*POCP_CO+FCH4D1*POCP_CH4+FN2OD1*POCP_N2O+FN
OxD1*POCP_NOx+FSO2D1*POCP_SO2+FHCD1*POCP_HC+FR134AD1*POCP_R;
NP=FCO2D1*NP_CO2    +FCOD1*NP_CO  +FCH4D1*NP_CH4  +FN2OD1*NP_N2O
+FNOxD1*NP_NOx  +FSO2D1*NP_SO2  +FHCD1*NP_HC  +FR134AD1*NP_R;
ATP=FCO2D1*ATP_CO2  +FCOD1*ATP_CO +FCH4D1*ATP_CH4 +FN2OD1*ATP_N2O
+FNOxD1*ATP_NOx +FSO2D1*ATP_SO2 +FHCD1*ATP_HC +FR134AD1*ATP_R;

!degree of satisfaction;
!lamda_macro=w_EC*lamda_EC+w_EN*lamda_EN;
!lamda_EC=(22085.02-C_Tr)/(22085.02-14650.11);
!lamda_EN=w_GWP*lamda_GWP+w_AP*lamda_AP+w_POCP*lamda_POCP+w_NP*lamda_
NP;
!lamda_GWP=(4373.419-GWP)/(4373.419-2428.643);
!lamda_AP=(8.35746-AP)/(8.35746-4.640828);
!lamda_POCP=(21.1128-POCP)/(21.1128-11.72434);
!lamda_NP=(0.956117-NP)/(9.56117-0.53095);
w_GWP=0.2; w_AP=0.2; w_POCP=0.2; w_NP=0.2; w_ATP=0.2;
w_EC=0.67; w_EN=0.33;
end
```

A.3.2 Lingo code for technology selection

```
max=lamda_micro;
!min=C_GP;!max=GWP;!min=Fwater;!max=AP;!min=ADP;!min=TTP;!max=ATP;
!max=NP;!max=POCP;!OPH=8640h/y;

!Input amount of each biomass, PD=paddy, SC=sugarcane,
PA=pineapple,OP=oilpalm;
!RH=rice husk, RS=rice straw, BG=baggase, PAW=peel, EFB=empty fruit
branch, PKS=palm kernel shell;
FPD=1.6426; ![t/h];
FRH=FPD*0.22;FRS=FPD*0.28;
FRH=FRH_PyF+FRH_PyS+FRH_Combust;
FRS=FRS_Combust+FRS_Cond;
FSC=1.3309; !t/h;
FBG=FSC*0.28;
FBG=FBG_DAcFer+FBG_DAlFer+FBG_HWFer+FBG_SEFer+FBG_Combust;
FPA=0.7249; !t/h;
FPAW=FPA*0.2;
FPAW=FPAW_AD+FPAW_Drying+FPAW_Fer;
FOP=1000; ![t/h];
FEFB=FOP*0.234;FPKS=FOP*0.073;
FEFB=FEFB_DLFPrd+FEFB_G+FEFB_Combust;
FPKS=FPKS_Briq+FPKS_Combust;

!Conversion;
X_oilF=500;       X_oilS=299;!L/t;
X_charF=0.15;     X_charS=0.35;!t/t;
X_syngasF=0.208;  X_syngasS=0.315;!m3/t;
X_Cond=0.7; ![t/t];
X_ethanolDAc=252.6;           X_ethanolDAl=255.8;
X_ethanolHW=255.3;            X_ethanolSE=230.2;   !L/t;
X_Biogas=55;!m3/t;X_BiogasElec=6;!kWh/m3;
X_AFeed=0.6;!t/t;X_CitricA=0.194;!t/t;
```

```
X_DLF=0.3752;           X_EP=0.33;!t/t;
X_SyngasG=0.427;![m3/t];  X_OilG=299;![L/t];   X_CharG=0.20; ![t/t];
X_RSCombust=4.79;![tHPS/t];X_RHCombust=5.99;![tHPS/t];
X_BGCombust=2.2;![tHPS/t];X_CombustElec=0.58; ![kW/t/h];
X_EFBCombust=2.59;![tHPS/t];X_PKSCombust=3.96;![tHPS/t];
Foil    = FRH_PyF*X_oilF    +FRH_PyS*X_oilS    +FEFB_G*X_OilG;
Fchar   = FRH_PyF*X_charF   +FRH_PyS*X_charS   +FEFB_G*X_CharG;
Fsyngas= FRH_PyF*X_syngasF +FRH_PyS*X_syngasS;
FAFeed= FRS_Cond*X_Cond+FPAW_Drying*X_AFeed;
FEthanol=FBG_DAcFer*X_ethanolDAc+FBG_DAlFer*X_ethanolDAl+FBG_HWFer*X_
ethanolHW+FBG_SEFer*X_ethanolSE;
FCitricA=FPAW_Fer*X_CitricA;
FDLF=FEFB_DLFPrd*X_DLF;
FEP=FPKS_Briq*X_EP;
FsyngasG=FEFB_G*X_SyngasG;

!Power Generation;
ElecGen=(FRS_Combust*X_RSCombust+FRH_Combust*X_RHCombust+FEFB_Combust
*X_EFBCombust+FPKS_Combust*X_PKSCombust+FBG_Combust*X_BGCombust)*X_Co
mbustElec+FPAW_AD*X_Biogas*X_BiogasElec;

!Elec requirement [kW/t/h];
Y_ElecPyF=180;    Y_ElecPyS=150;  Y_ElecCond=30;
Y_ElecDAcFer=58.19;      Y_ElecDAlFer=62.46;
Y_ElecHWFer=57.48;       Y_ElecSEFer=36.14;
Y_ElecFer=81.25;  Y_ElecDry=30;   Y_ElecAD=35;
Y_ElecDLF=220;    Y_ElecEP=140;   Y_ElecG=280;
Y_ElecCombust=0;
ElecReq=FRH_PyF*Y_ElecPyF+FRH_PyS*Y_ElecPyS+FRS_Cond*Y_ElecCond+FBG_D
AcFer*Y_ElecDAcFer+FBG_DAlFer*Y_ElecDAlFer+FBG_HWFer*Y_ElecHWFer+FBG_
SEFer*Y_ElecSEFer+FPAW_AD*Y_ElecAD+FPAW_Drying*Y_ElecDry+FPAW_Fer*Y_E
lecFer+FEFB_DLFPrd*Y_ElecDLF+FPKS_Briq*Y_ElecEP+FEFB_G*Y_ElecG+(FRS_C
ombust+FRH_Combust+FEFB_Combust+FPKS_Combust+FBG_Combust)*Y_ElecCombu
st;
ElecImp+ElecGen=ElecReq+ElecExp;
ElecImp=@if(ElecReq #LT# ElecGen,0,ElecReq-ElecGen);

!Economic data;
CF_RH= 90; CF_RS= 58.5; CF_BG= 10; CF_PAW= 10; CF_EFB=10.8; CF_PKS=
12.6; ![RM/t];
CF_oil=1.1;![RM/L];CF_char=1260;![RM/t];
CF_syngas=600; ![RM/m3];CF_AFeed=260; ![RM/t];
CF_Ethanol=3.04;![RM/L];CF_CitricA=2520;![RM/t];
CF_DLF=720;![RM/t];CF_EP=600;![RM/t];
CF_SyngasG=400;![RM/m3];CF_ElecImp= 0.55;![RM/kWh];
CF_ElecExp= 0.43;![RM/kWh];CF_PyF=312; CF_PyS=281;
CF_CombustRS=46.03; CF_Cond=60;CF_CombustRH=56.54; ![RM/t/h];
CF_DAcFer=445; CF_DAlFer=419; CF_HWFer=413.6; CF_SEFer=372;
CF_CombustBG=81.1;
CF_Fer=320; CF_Drying=60; CF_AD=375;
CF_DLFPrd=99; CF_Briq=93.6; CF_G=330; CF_CombustEFB=24.87;
CF_CombustPKS=38.05;

!Economic Performance;
C_GP=(Foil*CF_oil+Fchar*CF_char+Fsyngas*CF_syngas+FAFeed*CF_AFeed+FEt
hanol*CF_Ethanol+FCitricA*CF_CitricA+FDLF*CF_DLF+FEP*CF_EP+FsyngasG*C
F_SyngasG+ElecExp*CF_ElecExp-ElecImp*CF_ElecImp-FRH*CF_RH-FRS*CF_RS-
FRH_PyF*CF_PyF-FRH_PyS*CF_PyS-FRS_Cond*CF_Cond-FBG*CF_BG-
FBG_DAcFer*CF_DAcFer-FBG_DAlFer*CF_DAlFer-FBG_HWFer*CF_HWFer-
FBG_SEFer*CF_SEFer-FPAW*CF_PAW-FPAW_AD*CF_AD-FPAW_Drying*CF_Drying-
FPAW_Fer*CF_Fer-FEFB*CF_EFB-FPKS*CF_PKS-FEFB_DLFPrd*CF_DLFPrd-
```

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FPKS_Briq*CF_Briq-FEFB_G*CF_G-FRS_Combust*CF_CombustRS-
FRH_Combust*CF_CombustRH-FBG_Combust*CF_CombustBG-
FEFB_Combust*CF_CombustEFB-FPKS_Combust*CF_CombustPKS);![RM/h];
@free(C_GP);

!Environmental data;
X_CO2F=463;   X_CO2S=404;
X_COF=0.058;  X_COS=0.0549;
X_CH4F=0.003; X_CH4S=0.0037;
X_CO2DAcFer=1126;    X_CO2DAlFer=1205;  X_CO2HWFer=1154;
X_CO2SEFer=865.6;
X_CODAcFer=0.305;    X_CODAlFer=0.316;  X_COHWFer=0.324;
X_COSEFer=0.218;
X_CH4DAcFer=1.124;   X_CH4DAlFer=1.132; X_CH4HWFer=0.121;
X_CH4SEFer=1.1;
X_CO2Fer=300;    X_COFer=0.081;     X_CH4Fer=0.03;
!X_CO2AD=970;    !X_COAD=0.471;     !X_CH4AD=23;  ![g/kg];
X_CO2AD=0;    X_COAD=0;  X_CH4AD=0;
X_N2OAD=0.003;![g/kg];
X_CO2DLF=0; X_CO2EP=0; X_CO2G=588.6;
X_CODLF=0;  X_COEP=0;  X_COG=0.0803;
X_CH4DLF=0; X_CH4EP=0; X_CH4G=0.0054;
!X_CO2Combust=1585;    !X_COCombust=102;  !X_CH4Combust=5.82;![g/kg];
X_CO2Combust=0;    X_COCombust=0;  X_CH4Combust=0;  ![g/kg];
FCO2=FRH_PyF*X_CO2F+FRH_PyS*X_CO2S+FBG_DAcFer*X_CO2DAcFer+FBG_DAlFer*
X_CO2DAlFer+FBG_HWFer*X_CO2HWFer+FBG_SEFer*X_CO2SEFer+FPAW_AD*X_CO2AD
+FPAW_Fer*X_CO2Fer+FEFB_DLFPrd*X_CO2DLF+FPKS_Briq*X_CO2EP+FEFB_G*X_CO
2G+(FRS_Combust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_
CO2Combust;
FCO=FRH_PyF*X_COF+FRH_PyS*X_COS+FBG_DAcFer*X_CODAcFer+FBG_DAlFer*X_CO
DAlFer+FBG_HWFer*X_COHWFer+FBG_SEFer*X_COSEFer+FPAW_AD*X_COAD+FPAW_Fe
r*X_COFer+FEFB_DLFPrd*X_CODLF+FPKS_Briq*X_COEP+FEFB_G*X_COG+(FRS_Comb
ust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_COCombust;
FCH4=FRH_PyF*X_CH4F+FRH_PyS*X_CH4S+FBG_DAcFer*X_CH4DAcFer+FBG_DAlFer*
X_CH4DAlFer+FBG_HWFer*X_CH4HWFer+FBG_SEFer*X_CH4SEFer+FPAW_AD*X_CH4AD
+FPAW_Fer*X_CH4Fer+FEFB_DLFPrd*X_CH4DLF+FPKS_Briq*X_CH4EP+FEFB_G*X_CH
4G+(FRS_Combust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_
CH4Combust;
FN2O=FPAW_AD*X_N2OAD;  ![kg/h];
X_NOxF=0.0553;   X_NOxS=0.0549;
X_SO2F=0.0030;   X_SO2S=0.0037;
X_HCF=0.0030;    X_HCS=0.0037;
X_NOxDAcFer=0.305;    X_NOxDAlFer=0.312;  X_NOxHWFer=0.324;
X_NOxSEFer=0.218;
X_SO2DAcFer=0.775;    X_SO2DAlFer=0.675;  X_SO2HWFer=0.513;
X_SO2SEFer=0.796;
X_HCDAcFer=0;         X_HCDAlFer=0;       X_HCHWFer=0;
X_HCSEFer=0;
X_NOxFer=0.08;                X_SO2Fer=0.121;     X_HCFer=0;
X_NOxAD=0; !X_NOxAD=0.561;    X_SO2AD=0.121;
X_HCAD=0.4709;  ![g/kg];
X_NOxDLF=0;   X_NOxEP=0; X_NOxG=0.0803;
X_SO2DLF=0;   X_SO2EP=0; X_SO2G=0.0054;
X_HCDLF=0;    X_HCEP=0;  X_HCG=0.0054;
!X_NOxCombust=3.11;
X_NOxCombust=0;    X_SO2Combust=0;  X_HCCombust=25.406;  ![g/kg];
FNOX=FRH_PyF*X_NOXF+FRH_PyS*X_NOXS+FBG_DAcFer*X_NOXDAcFer+FBG_DAlFer*
X_NOXDAlFer+FBG_HWFer*X_NOXHWFer+FBG_SEFer*X_NOXSEFer+FPAW_AD*X_NOXAD
+FPAW_Fer*X_NOXFer+FEFB_DLFPrd*X_NOXDLF+FPKS_Briq*X_NOXEP+FEFB_G*X_NO
XG+(FRS_Combust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_
NOXCombust;
```

```
FSO2=FRH_PyF*X_SO2F+FRH_PyS*X_SO2S+FBG_DAcFer*X_SO2DAcFer+FBG_DAlFer*
X_SO2DAlFer+FBG_HWFer*X_SO2HWFer+FBG_SEFer*X_SO2SEFer+FPAW_AD*X_SO2AD
+FPAW_Fer*X_SO2Fer+FEFB_DLFPrd*X_SO2DLF+FPKS_Briq*X_SO2EP+FEFB_G*X_SO
2G+(FRS_Combust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_
SO2Combust;
FHC=FRH_PyF*X_HCF+FRH_PyS*X_HCS+FBG_DAcFer*X_HCDAcFer+FBG_DAlFer*X_HC
DAlFer+FBG_HWFer*X_HCHWFer+FBG_SEFer*X_HCSEFer+FPAW_AD*X_HCAD+FPAW_Fe
r*X_HCFer+FEFB_DLFPrd*X_HCDLF+FPKS_Briq*X_HCEP+FEFB_G*X_HCG+(FRS_Comb
ust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_HCCombust;
X_CODF=60;   X_CODS=60;
X_CODDAcFer=252.6;     X_CODDAlFer=255.8;   X_CODHWFer=255.3;
X_CODSEFer=230.2;
X_CODFer=263;     X_CODAD=-2.522;
X_CODDLF=60;   X_CODEP=0;   X_CODG=60;
X_CODCombust=0.02;  ![g/kg];
FCOD=FRH_PyF*X_CODF+FRH_PyS*X_CODS+FBG_DAcFer*X_CODDAcFer+FBG_DAlFer*
X_CODDAlFer+FBG_HWFer*X_CODHWFer+FBG_SEFer*X_CODSEFer+FPAW_AD*X_CODAD
+FPAW_Fer*X_CODFer+FEFB_DLFPrd*X_CODDLF+FPKS_Briq*X_CODEP+FEFB_G*X_CO
DG+(FRS_Combust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_
CODCombust;
@free(X_CODAD);@free(FCOD);
Y_WaterPyF=0.0231;     Y_WaterPyS=0.0231; ![m3/t];
Y_WaterDAcFer=0.1489; Y_WaterDAlFer=0.1510; Y_WaterHWFer=0.1685;
Y_WaterSEFer=0.1154;![m3/t];
Y_WaterFer=0.0214;     Y_WaterAD= 0; ![m3/t];
Y_WaterDLF=0;          Y_WaterEP=0;          Y_WaterG=0.138;![m3/t];
Y_WaterCombust= 1.8*10^-5; ![m3/kWh];
FWATER=FRH_PyF*Y_WaterPyF+FRH_PyS*Y_WaterPyS+FBG_DAcFer*Y_WaterDAcFer
+FBG_DAlFer*Y_WaterDAlFer+FBG_HWFer*Y_WaterHWFer+FBG_SEFer*Y_WaterSEF
er+FEFB_DLFPrd*Y_WaterDLF+FPKS_Briq*Y_WaterEP+FEFB_G*Y_WaterG+FPAW_AD
*Y_WaterAD+FPAW_Fer*Y_WaterFer+(FRS_Combust+FRH_Combust+FBG_Combust+F
EFB_Combust+FPKS_Combust)*Y_WaterCombust;![m3/h];

!PEI from WAR;
GWP_CO2=1;AP_CO2=0;POCP_CO2=0;NP_CO2=0;ATP_CO2=0;TTP_CO2=0;ADP_CO2=0;
GWP_CO=0;AP_CO=0;POCP_CO=0.01470;NP_CO=0;ATP_CO=0;TTP_CO=0;ADP_CO=0;
GWP_CH4=23;AP_CH4=0;POCP_CH4=0.00384;NP_CH4=0;ATP_CH4=0;TTP_CH4=0;ADP
_CH4=0;
GWP_NOx=0;AP_NOX=1.1;POCP_NOx=1.3;NP_NOx=0.13;ATP_NOx=0;TTP_NOx=0;ADP
_NOx=0;
GWP_N2O=296;AP_N2O=0.7;POCP_N2O=0.00384;NP_N2O=0;ATP_N2O=0;TTP_N2O=0;
ADP_N2O=0;
GWP_SO2=0;AP_SO2=1;POCP_SO2=0.125;NP_SO2=0;ATP_SO2=0;TTP_SO2=0;ADP_SO
2=0;
GWP_HC=0;AP_HC=0.018;POCP_HC=0.416;NP_HC=0;ATP_HC=0;TTP_HC=0;ADP_HC=0
;
GWP_COD=0;AP_COD=0;POCP_COD=0;NP_COD=0.022;ATP_COD=0;TTP_COD=0;ADP_CO
D=0; ![kg-eq/kg];
GWP_Coal=23.02;AP_Coal=0.177;POCP_Coal=0;NP_Coal=0;ATP_Coal=2.081*10^
-5;TTP_Coal=6.071*10^-6;ADP_Coal=0.0134;
GWP_Oil=0;AP_Oil=0;POCP_Oil=0.923;NP_Oil=0;ATP_Oil=0.16393;TTP_Oil=0.
00204;ADP_Oil=0;
GWP_Char=0;AP_Char=0;POCP_Char=0;NP_Char=0.5037;ATP_Char=8.4238;TTP_C
har=0.1687;ADP_Char=0;
GWP_SyngasF=9.156;AP_SyngasF=0;POCP_SyngasF=0.0636;NP_SyngasF=0;ATP_S
yngasF=0;TTP_SyngasF=0;ADP_SyngasF=0;
GWP_SyngasS=9.107;AP_SyngasS=0;POCP_SyngasS=0.0353;NP_SyngasS=0;ATP_S
yngasS=0;TTP_SyngasS=0;ADP_SyngasS=0;
GWP_AFeed=0;AP_AFeed=0;POCP_AFeed=0;NP_AFeed=0.503;ATP_AFeed=0;TTP_AF
eed=0;ADP_AFeed=0;
```

```
GWP_Ethanol=0;AP_Ethanol=0;POCP_Ethanol=0.407;NP_Ethanol=0;ATP_Ethano
l=0.00007;TTP_Ethanol=0.00011;ADP_Ethanol=0;
GWP_CitricA=0;AP_CitricA=0;POCP_CitricA=0.407;NP_CitricA=0;ATP_Citric
A=0.00361;TTP_CitricA=0.00015;ADP_CitricA=0;
GWP_DLF=0;AP_DLF=0;POCP_DLF=0;NP_DLF=0;ATP_DLF=0;TTP_DLF=0;ADP_DLF=0;
GWP_EP=0;AP_EP=0;POCP_EP=0.923;NP_EP=0;ATP_EP=0.16393;TTP_EP=0.00204;
ADP_EP=0;
GWP_SyngasG=0.6248;AP_SyngasG=0;POCP_SyngasG=0.0038;NP_SyngasG=0;ATP_
SyngasG=0;TTP_SyngasG=0;ADP_SyngasG=0;

!Environmental performance;
FCoal=ElecImp/8.141;
!FCoal_Sub=ElecGen/8.141;
FCoal_Sub=ElecGen/8.141+(Foil*21.6+FRH_PyF*X_syngasF*19.566
+FRH_PyS*X_syngasS*20.286+FEthanol*21+FEP*21*1000+FsyngasG*10.935)/29
.308;
FCoal_Sub_Elec=ElecGen/8.141;
!Biooil-to-power:21.6MJ/L;
!Syngas-to-power:19.566MJ/m3 (fast) 20.286/mj/m3 (slow);
!Coal-to-power:29.308 MJ/kg or 8.141 kWh/kg;

GWP= (FCO2*GWP_CO2 +FCO*GWP_CO+FCH4*GWP_CH4+FN2O*GWP_N2O+FNOx*GWP_NOx
+FSO2*GWP_SO2+FHC*GWP_HC+FCOD*GWP_COD+FOil*1.17*GWP_Oil+FChar*1000*GW
P_Char+FRH_PyF*X_syngasF*0.95*GWP_SyngasF+FRH_PyS*X_syngasS*0.95*GWP_
SyngasS+FAFeed*1000*GWP_AFeed+FEthanol*0.789*GWP_Ethanol+FCitricA*GWP
_CitricA*1000+FDLF*1000*GWP_DLF+FEP*1000*GWP_EP+FsyngasG*0.95*GWP_syn
gasG +(FCoal-FCoal_Sub)*GWP_Coal);

AP=  (FCO2*AP_CO2  +FCO*AP_CO  +FCH4*AP_CH4  +FN2O*AP_N2O+FNOx*AP_NOx
+FSO2*AP_SO2+FHC*AP_HC+FCOD*AP_COD+FOil*1.17*AP_Oil+FChar*1000*AP_Cha
r+FRH_PyF*X_syngasF*0.95*AP_SyngasF+FRH_PyS*X_syngasS*0.95*AP_SyngasS
+FAFeed*1000*AP_AFeed+FEthanol*0.789*AP_Ethanol+FCitricA*AP_CitricA*1
000+FDLF*1000*AP_DLF+FEP*1000*AP_EP+FsyngasG*0.95*AP_syngasG+(FCoal-
FCoal_Sub)*AP_Coal);

POCP=(FCO2*POCP_CO2+FCO*POCP_CO+FCH4*POCP_CH4+FN2O*POCP_N2O+FNOx*POCP
_NOx+FSO2*POCP_SO2+FHC*POCP_HC+FCOD*POCP_COD+FOil*1.17*POCP_Oil+FChar
*1000*POCP_Char+FRH_PyF*X_syngasF*0.95*POCP_SyngasF+FRH_PyS*X_syngasS
*0.95*POCP_SyngasS+FAFeed*1000*POCP_AFeed+FEthanol*0.789*POCP_Ethanol
+FCitricA*POCP_CitricA*1000+FDLF*1000*POCP_DLF+FEP*1000*POCP_EP+Fsyng
asG*0.95*POCP_syngasG+(FCoal-FCoal_Sub)*POCP_Coal);

NP=  (FCO2*NP_CO2  +FCO*NP_CO  +FCH4*NP_CH4  +FN2O*NP_N2O+FNOx*NP_NOx
+FSO2*NP_SO2+FHC*NP_HC+FCOD*NP_COD+FOil*1.17*NP_Oil+FChar*1000*NP_Cha
r+FRH_PyF*X_syngasF*0.95*NP_SyngasF+FRH_PyS*X_syngasS*0.95*NP_SyngasS
+FAFeed*1000*NP_AFeed+FEthanol*0.789*NP_Ethanol+FCitricA*NP_CitricA*1
000+FDLF*1000*NP_DLF+FEP*1000*NP_EP+FsyngasG*0.95*NP_syngasG+(FCoal-
FCoal_Sub)*NP_Coal);

ATP=(FCO2*ATP_CO2+FCO*ATP_CO+FCH4*ATP_CH4+FN2O*ATP_N2O+FNOx*ATP_NOx+F
SO2*ATP_SO2+FHC*ATP_HC+FCOD*ATP_COD+FOil*1.17*ATP_Oil+FChar*1000*ATP_
Char+FRH_PyF*X_syngasF*0.95*ATP_SyngasF+FRH_PyS*X_syngasS*0.95*ATP_Sy
ngasS+FAFeed*1000*ATP_AFeed+FEthanol*0.789*ATP_Ethanol+FCitricA*ATP_C
itricA*1000 +FDLF*1000*ATP_DLF +FEP*1000*ATP_EP
+FsyngasG*0.95*ATP_syngasG +(FCoal-FCoal_Sub)*ATP_Coal);

TTP= (FCO2*TTP_CO2 +FCO*TTP_CO+FCH4*TTP_CH4+FN2O*TTP_N2O+FNOx*TTP_NOx
+FSO2*TTP_SO2+FHC*TTP_HC+FCOD*TTP_COD+FOil*1.17*TTP_Oil+FChar*1000*TT
P_Char+FRH_PyF*X_syngasF*0.95*TTP_SyngasF+FRH_PyS*X_syngasS*0.95*TTP_
SyngasS+FAFeed*1000*TTP_AFeed+FEthanol*0.789*TTP_Ethanol+FCitricA*TTP
```

```
_CitricA*1000+FDLF*1000*TTP_DLF+FEP*1000*TTP_EP+FsyngasG*0.95*TTP_syn
gasG +(FCoal-FCoal_Sub)*TTP_Coal);

ADP= (FCO2*ADP_CO2 +FCO*ADP_CO+FCH4*ADP_CH4+FN2O*ADP_N2O+FNOx*ADP_NOx
+FSO2*ADP_SO2+FHC*ADP_HC+FCOD*ADP_COD+FOil*1.17*ADP_Oil+FChar*1000*AD
P_Char+FRH_PyF*X_syngasF*0.95*ADP_SyngasF+FRH_PyS*X_syngasS*0.95*ADP_
SyngasS+FAFeed*1000*ADP_AFeed+FEthanol*0.789*ADP_Ethanol+FCitricA*ADP
_CitricA*1000+FDLF*1000*ADP_DLF+FEP*1000*ADP_EP+FsyngasG*0.95*ADP_syn
gasG+(FCoal-FCoal_Sub)*ADP_Coal);
@free(GWP);@free(AP);@free(POCP);@free(NP);@free(ATP);@free(TTP);@fre
e(ADP);


!Sustainability measurement;
lamda_micro=w_EC*lamda_EC+w_EN*lamda_EN;
lamda_EC=@if(C_GP#LT#0,0,C_GP/61535.4);
lamda_EN=w_GWP*lamda_GWP+w_AP*lamda_AP+w_POCP*lamda_POCP+w_NP*lamda_N
P+w_ATP*lamda_ATP+w_TTP*lamda_TTP+w_ADP*lamda_ADP+w_water*lamda_water
;

!degree of satisfaction for each impact;
lamda_GWP=(144727-GWP)/(144727-(-1237304));
lamda_AP=(1146.21-AP)/(1146.21-(-10555.36));
lamda_POCP=(98060.1-POCP)/(98060.1);
lamda_NP=(24156.52-NP)/(24156.52);
lamda_ATP=(412687.4-ATP)/(412687.4-(-0.00146));
lamda_TTP=(8132.55-TTP)/(8132.55-(-0.00043));
lamda_ADP=(84.22-ADP)/(84.22-(-800.812));
lamda_water=(32.368-FWater)/(32.368);

!relative importance, exte=racted from AHP results;
w_GWP=0.2396;w_AP=0.0948;w_POCP=0.0371;w_NP=0.0371;
w_ATP=0.2165;w_TTP=0.2165;w_ADP=0.1027;w_water=0.0557;
w_EC=0.67;w_EN=0.33;

end
```

A.3.3 Optimised result (technology selection)

```
Global optimal solution found.
  Objective value:                              0.8141216
  Objective bound:                              0.8141216
  Infeasibilities:                               0.000000
  Extended solver steps:                                0
  Total solver iterations:                             22
  Elapsed runtime seconds:                           0.48

  Model Class:                                        NLP

  Total variables:                     62
  Nonlinear variables:                  3
  Integer variables:                    0

  Total constraints:                   51
  Nonlinear constraints:                2

  Total nonzeros:                     288
  Nonlinear nonzeros:                   3
```

Variable	Value	Reduced Cost
LAMDA_MICRO	0.8141216	0.000000
FPD	1.642600	0.000000
FRH	0.3613720	0.000000
FRS	0.4599280	0.000000
FRH_PYF	0.000000	0.000000
FRH_PYS	0.3613720	0.000000
FRH_COMBUST	0.000000	0.000000
FRS_COMBUST	0.000000	0.000000
FRS_COND	0.4599280	0.000000
FSC	1.330900	0.000000
FBG	0.3726520	0.000000
FBG_DACFER	0.000000	0.000000
FBG_DALFER	0.000000	0.000000
FBG_HWFER	0.3726520	0.000000
FBG_SEFER	0.000000	0.000000
FBG_COMBUST	0.000000	0.000000
FPA	0.7249000	0.000000
FPAW	0.1449800	0.000000
FPAW_AD	0.000000	0.000000
FPAW_DRYING	0.000000	0.000000
FPAW_FER	0.1449800	0.000000
FOP	1000.000	0.000000
FEFB	234.0000	0.000000
FPKS	73.00000	0.000000
FEFB_DLFPRD	0.000000	0.000000
FEFB_G	234.0000	0.000000
FEFB_COMBUST	0.000000	0.000000
FPKS_BRIQ	73.00000	0.000000
FPKS_COMBUST	0.000000	0.000000
X_OILF	500.0000	0.000000
X_OILS	299.0000	0.000000
X_CHARF	0.1500000	0.000000
X_CHARS	0.3500000	0.000000
X_SYNGASF	0.2080000	0.000000
X_SYNGASS	0.3150000	0.000000
X_COND	0.7000000	0.000000
X_ETHANOLDAC	252.6000	0.000000
X_ETHANOLDAL	255.8000	0.000000
X_ETHANOLHW	255.3000	0.000000
X_ETHANOLSE	230.2000	0.000000
X_BIOGAS	55.00000	0.000000
X_BIOGASELEC	6.000000	0.000000
X_AFEED	0.6000000	0.000000
X_CITRICA	0.1940000	0.000000
X_DLF	0.3752000	0.000000
X_EP	0.3300000	0.000000
X_SYNGASG	0.4270000	0.000000
X_OILG	299.0000	0.000000
X_CHARG	0.2000000	0.000000
X_RSCOMBUST	4.790000	0.000000
X_RHCOMBUST	5.990000	0.000000
X_BGCOMBUST	2.200000	0.000000
X_COMBUSTELEC	0.5800000	0.000000
X_EFBCOMBUST	2.590000	0.000000
X_PKSCOMBUST	3.960000	0.000000
FOIL	70074.05	0.000000
FCHAR	46.92648	0.000000
FSYNGAS	0.1138322	0.000000

FAFEED	0.3219496	0.000000
FETHANOL	95.13806	0.000000
FCITRICA	0.2812612E-01	0.000000
FDLF	0.000000	0.000000
FEP	24.09000	0.000000
FSYNGASG	99.91800	0.000000
ELECGEN	0.000000	0.000000
Y_ELECPYF	180.0000	0.000000
Y_ELECPYS	150.0000	0.000000
Y_ELECCOND	30.00000	0.000000
Y_ELECDACFER	58.19000	0.000000
Y_ELECDALFER	62.46000	0.000000
Y_ELECHWFER	57.48000	0.000000
Y_ELECSEFER	36.14000	0.000000
Y_ELECFER	81.25000	0.000000
Y_ELECDRY	30.00000	0.000000
Y_ELECAD	35.00000	0.000000
Y_ELECDLF	220.0000	0.000000
Y_ELECEP	140.0000	0.000000
Y_ELECG	280.0000	0.000000
Y_ELECCOMBUST	0.000000	0.000000
ELECREQ	75841.20	0.000000
ELECIMP	75841.20	0.000000
ELECEXP	0.000000	0.000000
CF_RH	90.00000	0.000000
CF_RS	58.50000	0.000000
CF_BG	10.00000	0.000000
CF_PAW	10.00000	0.000000
CF_EFB	10.80000	0.000000
CF_PKS	12.60000	0.000000
CF_OIL	1.100000	0.000000
CF_CHAR	1260.000	0.000000
CF_SYNGAS	600.0000	0.000000
CF_AFEED	260.0000	0.000000
CF_ETHANOL	3.040000	0.000000
CF_CITRICA	2520.000	0.000000
CF_DLF	720.0000	0.000000
CF_EP	600.0000	0.000000
CF_SYNGASG	400.0000	0.000000
CF_ELECIMP	0.5500000	0.000000
CF_ELECEXP	0.4300000	0.000000
CF_PYF	312.0000	0.000000
CF_PYS	281.0000	0.000000
CF_COMBUSTRS	46.03000	0.000000
CF_COND	60.00000	0.000000
CF_COMBUSTRH	56.54000	0.000000
CF_DACFER	445.0000	0.000000
CF_DALFER	419.0000	0.000000
CF_HWFER	413.6000	0.000000
CF_SEFER	372.0000	0.000000
CF_COMBUSTBG	81.10000	0.000000
CF_FER	320.0000	0.000000
CF_DRYING	60.00000	0.000000
CF_AD	375.0000	0.000000
CF_DLFPRD	99.00000	0.000000
CF_BRIQ	93.60000	0.000000
CF_G	330.0000	0.000000
CF_COMBUSTEFB	24.87000	0.000000
CF_COMBUSTPKS	38.05000	0.000000
C_GP	61535.39	0.000000
X_CO2F	463.0000	0.000000

X_CO2S	404.0000	0.000000
X_COF	0.5800000E-01	0.000000
X_COS	0.5490000E-01	0.000000
X_CH4F	0.3000000E-02	0.000000
X_CH4S	0.3700000E-02	0.000000
X_CO2DACFER	1126.000	0.000000
X_CO2DALFER	1205.000	0.000000
X_CO2HWFER	1154.000	0.000000
X_CO2SEFER	865.6000	0.000000
X_CODACFER	0.3050000	0.000000
X_CODALFER	0.3160000	0.000000
X_COHWFER	0.3240000	0.000000
X_COSEFER	0.2180000	0.000000
X_CH4DACFER	1.124000	0.000000
X_CH4DALFER	1.132000	0.000000
X_CH4HWFER	0.1210000	0.000000
X_CH4SEFER	1.100000	0.000000
X_CO2FER	300.0000	0.000000
X_COFER	0.8100000E-01	0.000000
X_CH4FER	0.3000000E-01	0.000000
X_CO2AD	0.000000	0.000000
X_COAD	0.000000	0.000000
X_CH4AD	0.000000	0.000000
X_N2OAD	0.3000000E-02	0.000000
X_CO2DLF	0.000000	0.000000
X_CO2EP	0.000000	0.000000
X_CO2G	588.6000	0.000000
X_CODLF	0.000000	0.000000
X_COEP	0.000000	0.000000
X_COG	0.8030000E-01	0.000000
X_CH4DLF	0.000000	0.000000
X_CH4EP	0.000000	0.000000
X_CH4G	0.5400000E-02	0.000000
X_CO2COMBUST	0.000000	0.000000
X_COCOMBUST	0.000000	0.000000
X_CH4COMBUST	0.000000	0.000000
FCO2	138351.9	0.000000
FCO	18.94252	0.000000
FCH4	1.314377	0.000000
FN2O	0.000000	0.000000
X_NOXF	0.5530000E-01	0.000000
X_NOXS	0.5490000E-01	0.000000
X_SO2F	0.3000000E-02	0.000000
X_SO2S	0.3700000E-02	0.000000
X_HCF	0.3000000E-02	0.000000
X_HCS	0.3700000E-02	0.000000
X_NOXDACFER	0.3050000	0.000000
X_NOXDALFER	0.3120000	0.000000
X_NOXHWFER	0.3240000	0.000000
X_NOXSEFER	0.2180000	0.000000
X_SO2DACFER	0.7750000	0.000000
X_SO2DALFER	0.6750000	0.000000
X_SO2HWFER	0.5130000	0.000000
X_SO2SEFER	0.7960000	0.000000
X_HCDACFER	0.000000	0.000000
X_HCDALFER	0.000000	0.000000
X_HCHWFER	0.000000	0.000000
X_HCSEFER	0.000000	0.000000
X_NOXFER	0.8000000E-01	0.000000
X_SO2FER	0.1210000	0.000000
X_HCFER	0.000000	0.000000

X_NOXAD	0.000000	0.000000
X_SO2AD	0.1210000	0.000000
X_HCAD	0.4709000	0.000000
X_NOXDLF	0.000000	0.000000
X_NOXEP	0.000000	0.000000
X_NOXG	0.8030000E-01	0.000000
X_SO2DLF	0.000000	0.000000
X_SO2EP	0.000000	0.000000
X_SO2G	0.5400000E-02	0.000000
X_HCDLF	0.000000	0.000000
X_HCEP	0.000000	0.000000
X_HCG	0.5400000E-02	0.000000
X_NOXCOMBUST	0.000000	0.000000
X_SO2COMBUST	0.000000	0.000000
X_HCCOMBUST	25.40600	0.000000
FNOX	18.94238	0.000000
FSO2	1.473650	0.000000
FHC	1.264937	0.000000
X_CODF	60.00000	0.000000
X_CODS	60.00000	0.000000
X_CODDACFER	252.6000	0.000000
X_CODDALFER	255.8000	0.000000
X_CODHWFER	255.3000	0.000000
X_CODSEFER	230.2000	0.000000
X_CODFER	263.0000	0.000000
X_CODAD	-2.522000	0.000000
X_CODDLF	60.00000	0.000000
X_CODEP	0.000000	0.000000
X_CODG	60.00000	0.000000
X_CODCOMBUST	0.2000000E-01	0.000000
FCOD	14194.95	0.000000
Y_WATERPYF	0.2310000E-01	0.000000
Y_WATERPYS	0.2310000E-01	0.000000
Y_WATERDACFER	0.1489000	0.000000
Y_WATERDALFER	0.1510000	0.000000
Y_WATERHWFER	0.1685000	0.000000
Y_WATERSEFER	0.1154000	0.000000
Y_WATERFER	0.2140000E-01	0.000000
Y_WATERAD	0.000000	0.000000
Y_WATERDLF	0.000000	0.000000
Y_WATEREP	0.000000	0.000000
Y_WATERG	0.1380000	0.000000
Y_WATERCOMBUST	0.1800000E-04	0.000000
FWATER	32.36624	0.000000
GWP_CO2	1.000000	0.000000
AP_CO2	0.000000	0.000000
POCP_CO2	0.000000	0.000000
NP_CO2	0.000000	0.000000
ATP_CO2	0.000000	0.000000
TTP_CO2	0.000000	0.000000
ADP_CO2	0.000000	0.000000
GWP_CO	0.000000	0.000000
AP_CO	0.000000	0.000000
POCP_CO	0.1470000E-01	0.000000
NP_CO	0.000000	0.000000
ATP_CO	0.000000	0.000000
TTP_CO	0.000000	0.000000
ADP_CO	0.000000	0.000000
GWP_CH4	23.00000	0.000000
AP_CH4	0.000000	0.000000
POCP_CH4	0.3840000E-02	0.000000

NP_CH4	0.000000	0.000000
ATP_CH4	0.000000	0.000000
TTP_CH4	0.000000	0.000000
ADP_CH4	0.000000	0.000000
GWP_NOX	0.000000	0.000000
AP_NOX	1.100000	0.000000
POCP_NOX	1.300000	0.000000
NP_NOX	0.1300000	0.000000
ATP_NOX	0.000000	0.000000
TTP_NOX	0.000000	0.000000
ADP_NOX	0.000000	0.000000
GWP_N2O	296.0000	0.000000
AP_N2O	0.7000000	0.000000
POCP_N2O	0.3840000E-02	0.000000
NP_N2O	0.000000	0.000000
ATP_N2O	0.000000	0.000000
TTP_N2O	0.000000	0.000000
ADP_N2O	0.000000	0.000000
GWP_SO2	0.000000	0.000000
AP_SO2	1.000000	0.000000
POCP_SO2	0.1250000	0.000000
NP_SO2	0.000000	0.000000
ATP_SO2	0.000000	0.000000
TTP_SO2	0.000000	0.000000
ADP_SO2	0.000000	0.000000
GWP_HC	0.000000	0.000000
AP_HC	0.1800000E-01	0.000000
POCP_HC	0.4160000	0.000000
NP_HC	0.000000	0.000000
ATP_HC	0.000000	0.000000
TTP_HC	0.000000	0.000000
ADP_HC	0.000000	0.000000
GWP_COD	0.000000	0.000000
AP_COD	0.000000	0.000000
POCP_COD	0.000000	0.000000
NP_COD	0.2200000E-01	0.000000
ATP_COD	0.000000	0.000000
TTP_COD	0.000000	0.000000
ADP_COD	0.000000	0.000000
GWP_COAL	23.02000	0.000000
AP_COAL	0.1770000	0.000000
POCP_COAL	0.000000	0.000000
NP_COAL	0.000000	0.000000
ATP_COAL	0.2081000E-04	0.000000
TTP_COAL	0.6071000E-05	0.000000
ADP_COAL	0.1340000E-01	0.000000
GWP_OIL	0.000000	0.000000
AP_OIL	0.000000	0.000000
POCP_OIL	0.9230000	0.000000
NP_OIL	0.000000	0.000000
ATP_OIL	0.1639300	0.000000
TTP_OIL	0.2040000E-02	0.000000
ADP_OIL	0.000000	0.000000
GWP_CHAR	0.000000	0.000000
AP_CHAR	0.000000	0.000000
POCP_CHAR	0.000000	0.000000
NP_CHAR	0.5037000	0.000000
ATP_CHAR	8.423800	0.000000
TTP_CHAR	0.1687000	0.000000
ADP_CHAR	0.000000	0.000000
GWP_SYNGASF	9.156000	0.000000

AP_SYNGASF	0.000000	0.000000
POCP_SYNGASF	0.6360000E-01	0.000000
NP_SYNGASF	0.000000	0.000000
ATP_SYNGASF	0.000000	0.000000
TTP_SYNGASF	0.000000	0.000000
ADP_SYNGASF	0.000000	0.000000
GWP_SYNGASS	9.107000	0.000000
AP_SYNGASS	0.000000	0.000000
POCP_SYNGASS	0.3530000E-01	0.000000
NP_SYNGASS	0.000000	0.000000
ATP_SYNGASS	0.000000	0.000000
TTP_SYNGASS	0.000000	0.000000
ADP_SYNGASS	0.000000	0.000000
GWP_AFEED	0.000000	0.000000
AP_AFEED	0.000000	0.000000
POCP_AFEED	0.000000	0.000000
NP_AFEED	0.5030000	0.000000
ATP_AFEED	0.000000	0.000000
TTP_AFEED	0.000000	0.000000
ADP_AFEED	0.000000	0.000000
GWP_ETHANOL	0.000000	0.000000
AP_ETHANOL	0.000000	0.000000
POCP_ETHANOL	0.4070000	0.000000
NP_ETHANOL	0.000000	0.000000
ATP_ETHANOL	0.7000000E-04	0.000000
TTP_ETHANOL	0.1100000E-03	0.000000
ADP_ETHANOL	0.000000	0.000000
GWP_CITRICA	0.000000	0.000000
AP_CITRICA	0.000000	0.000000
POCP_CITRICA	0.4070000	0.000000
NP_CITRICA	0.000000	0.000000
ATP_CITRICA	0.3610000E-02	0.000000
TTP_CITRICA	0.1500000E-03	0.000000
ADP_CITRICA	0.000000	0.000000
GWP_DLF	0.000000	0.000000
AP_DLF	0.000000	0.000000
POCP_DLF	0.000000	0.000000
NP_DLF	0.000000	0.000000
ATP_DLF	0.000000	0.000000
TTP_DLF	0.000000	0.000000
ADP_DLF	0.000000	0.000000
GWP_EP	0.000000	0.000000
AP_EP	0.000000	0.000000
POCP_EP	0.9230000	0.000000
NP_EP	0.000000	0.000000
ATP_EP	0.1639300	0.000000
TTP_EP	0.2040000E-02	0.000000
ADP_EP	0.000000	0.000000
GWP_SYNGASG	0.6248000	0.000000
AP_SYNGASG	0.000000	0.000000
POCP_SYNGASG	0.3800000E-02	0.000000
NP_SYNGASG	0.000000	0.000000
ATP_SYNGASG	0.000000	0.000000
TTP_SYNGASG	0.000000	0.000000
ADP_SYNGASG	0.000000	0.000000
FCOAL	9315.957	0.000000
FCOAL_SUB	69011.27	0.000000
FCOAL_SUB_ELEC	0.000000	0.000000
GWP	-1235744.	0.000000
AP	-10543.74	0.000000
POCP	97976.72	0.000000

NP	24113.56	0.000000
ATP	412687.3	0.000000
TTP	8132.544	0.000000
ADP	-799.9172	0.000000
W_EC	0.6700000	0.000000
LAMDA_EC	0.9999999	0.000000
W_EN	0.3300000	0.000000
LAMDA_EN	0.4367323	0.000000
W_GWP	0.2396000	0.000000
LAMDA_GWP	0.9988710	0.000000
W_AP	0.9480000E-01	0.000000
LAMDA_AP	0.9990067	0.000000
W_POCP	0.3710000E-01	0.000000
LAMDA_POCP	0.8503003E-03	0.000000
W_NP	0.3710000E-01	0.000000
LAMDA_NP	0.1778396E-02	0.000000
W_ATP	0.2165000	0.000000
LAMDA_ATP	0.2621061E-06	0.000000
W_TTP	0.2165000	0.000000
LAMDA_TTP	0.7846828E-06	0.000000
W_ADP	0.1027000	0.000000
LAMDA_ADP	0.9989890	0.000000
W_WATER	0.5570000E-01	0.000000
LAMDA_WATER	0.5430897E-04	0.000000

A.4 Appendix for Chapter 7

A.4.1 Analytical Hierarchy Process (AHP) Questionnaire

Questionnaire

We are conducting a research on identifying the relative importance of each sustainability dimension for biomass supply chain in Malaysia. By keeping it in view, please mark the relative importance of each dimension below in questions when it compared to other dimensions.

Sustainability Dimension

Question	Dimension A	Extremely more important to	Very strongly more important to	Strongly more Important to	Moderately more important to	Weakly more important to	Equal important to	Weakly less important to	Moderately less important to	Strongly less important to	Very strongly more important to	Extremely less important to	Dimension B
1	Economic Potential	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Environmnetal Impact
2	Environmnetal Impact	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Social Impact
3	Social Impact	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Social Impact
Note		A > B							B > A				

Figure A.3: AHP Questionnaire.

A.4.2 Lingo code (transportation design)

```
!max=lamda_macro;
min=C_Tr;
!min=GWP;!min=AP;!min=POCP;!min=NP;!max=ATP;!min=C_Tr;!max=GWP;
@free(C_Tr);@free(GWP); @free(AP);  @free(POCP); @free(NP);
@free(ATP);

!Input data;
F=0.15;![t/d];D1=44.3;![km];
F=F1M1+F1M2+F1M3+F1M4;

!Cap=capacity constraint, Sp=speed,DT=delay time;
CapM1=5;CapM2=10;CapM3=15.12;CapM4=30.4; ![t/vehicle];
SpM1=60;SPM2=60;SPM3=60;SPM4=60;
DTM1=0.33;DTM2=0.67;DTM3=1;DTM4=1.33;

!Maximum trip per day;
Trip_max_D1M1=@rounddown(20/((2*D1)/SpM1+DTM1),0);
Trip_max_D1M2=@rounddown(20/((2*D1)/SpM2+DTM2),0);
Trip_max_D1M3=@rounddown(20/((2*D1)/SpM3+DTM3),0);
Trip_max_D1M4=@rounddown(20/((2*D1)/SpM4+DTM4),0);


!Number of trip required;
Trip_req_M1=@roundup(F/CapM1,0); Trip_req_M2=@roundup(F/CapM2,0);
Trip_req_M3=@roundup(F/CapM3,0); Trip_req_M4=@roundup(F/CapM4,0);

!number of vehicle required;
n_D1M1=@roundup(Trip_req_M1/Trip_max_D1M1,0);
n_D1M2=@roundup(Trip_req_M2/Trip_max_D1M2,0);
n_D1M3=@roundup(Trip_req_M3/Trip_max_D1M3,0);
n_D1M4=@roundup(Trip_req_M4/Trip_max_D1M4,0);

!Big M determination;
M=100000;
F1M1<M*B11;  F1M2<M*B12;  F1M3<M*B13;  F1M4<M*B14;
B11+B12+B13+B14=1;
@bin(B11);@bin(B12);@bin(B13);@bin(B14);

!Economic Performance;
LS=10;![y];  OPD=355;![d/y]; HW=20;![RM/h]; C_Fuel=1.90;![RM/L];

!C_M=procurement cost, Fuel_cons=consumption rate, C_Main=maintenance
cost,C_Mile=mileague;
C_M1=70000; C_M2=90000; C_M3=125000; C_M4=150000;![RM];
Fuel_consM1=0.213; Fuel_consM2=0.213; Fuel_consM3=0.235;
Fuel_consM4=0.235; ![L/km];
C_MainM1=0.18; C_MainM2=0.22; C_MainM3=0.34; C_MainM4=0.45; ![RM/km];
C_Tr=C_OPEXD1+C_CAPEXD1;
C_CAPEXD1=(B11*n_D1M1*C_M1+B12*n_D1M2*C_M2+B13*n_D1M3*C_M3+B14*n_D1M4
*C_M4)/LS;
C_OPEXD1=C_LabourD1+C_MileD1+C_MaintainD1;
C_LabourD1=OPD*HW*(B11*Trip_req_M1*((2*D1)/SpM1+DTM1)+B12*Trip_req_M2
*((2*D1)/SpM2+DTM2)+B13*Trip_req_M3*((2*D1)/SpM3+DTM3)+B14*Trip_req_M
4*((2*D1)/SpM4+DTM4));
C_MileD1=2*C_Fuel*OPD*(B11*Trip_req_M1*D1*Fuel_consM1+B12*Trip_req_M2
*D1*Fuel_consM2+B13*Trip_req_M3*D1*Fuel_consM3+B14*Trip_req_M4*D1*Fue
l_consM4);
```

```
C_MaintainD1=2*OPD*(B11*Trip_req_M1*D1*C_MainM1+B12*Trip_req_M2*D1*C_
MainM2+B13*Trip_req_M3*D1*C_MainM3+B14*Trip_req_M4*D1*C_MainM4);

!Environmental Performance;
XCO2=2.6; XCH4=0.00056; XCO=0.2768; XN2O=0.000028;![kg/L];
XR134A=0.088; ![kg/vehicle/y];
XNOx=0.004408; XSO2=0.000017; XHC=0.006851;
FCO2D1=2*D1*OPD*XCO2*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fue
l_consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FCH4D1=2*D1*OPD*XCH4*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fue
l_consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FCOD1=2*D1*OPD*XCO*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fuel_
consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FN2OD1=2*D1*OPD*XN2O*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fue
l_consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FNOxD1=2*D1*OPD*XNOx*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fue
l_consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FSO2D1=2*D1*OPD*XSO2*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fue
l_consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FHCD1=2*D1*OPD*XHC*(B11*Trip_req_M1*Fuel_consM1+B12*Trip_req_M2*Fuel_
consM2+B13*Trip_req_M3*Fuel_consM3+B14*Trip_req_M4*Fuel_consM4);
FR134AD1=XR134A*(B11*n_D1M1+B12*n_D1M2+B13*n_D1M3+B14*n_D1M4);

!PEI (WAR)GWP:global warming potential, POCP:photochemical ozone
creation potential, NP:neutrification potential, ATP:Aquatic toxicity
potential, HTPE:human toxicity potential;
GWP_CO2=1;AP_CO2=0;POCP_CO2=0;NP_CO2=0;ATP_CO2=0;HTPE_CO2=0.00011111;
GWP_CO=0;AP_CO=0;POCP_CO=0.01470;NP_CO=0;ATP_CO=0;HTPE_CO=0.1818182;
GWP_CH4=23;AP_CH4=0;POCP_CH4=0.00384;NP_CH4=0;ATP_CH4=0;HTPE_CH4=0.00
151515;
GWP_NOx=0;AP_NOX=1.1;POCP_NOx=1.3;NP_NOx=0.13;ATP_NOx=0;HTPE_NOx=0;
GWP_N2O=296;AP_N2O=0.7;POCP_N2O=0.00384;NP_N2O=0;ATP_N2O=0;HTPE_N2O=0
.011111;
GWP_SO2=0;AP_SO2=1;POCP_SO2=0.125;NP_SO2=0;ATP_SO2=0;HTPE_SO2=0.07692
308;
GWP_HC=0;AP_HC=0.018;POCP_HC=0.416;NP_HC=0;ATP_HC=0;HTPE_HC=0;
GWP_R=1320;AP_R=0;POCP_R=0.0025;NP_R=0;ATP_R=0.00205338;HTPE_R=0;
ADP_Fuel=0.016723;
GWP=FCO2D1*GWP_CO2+FCOD1*GWP_CO+FCH4D1*GWP_CH4+FN2OD1*GWP_N2O+FNOxD1*
GWP_NOx +FSO2D1*GWP_SO2 +FHCD1*GWP_HC +FR134AD1*GWP_R;
AP=FCO2D1*AP_CO2+FCOD1*AP_CO+FCH4D1*AP_CH4+FN2OD1*AP_N2O+FNOxD1*AP_NO
x  +FSO2D1*AP_SO2  +FHCD1*AP_HC  +FR134AD1*AP_R;
POCP=FCO2D1*POCP_CO2+FCOD1*POCP_CO+FCH4D1*POCP_CH4+FN2OD1*POCP_N2O+FN
OxD1*POCP_NOx+FSO2D1*POCP_SO2+FHCD1*POCP_HC+FR134AD1*POCP_R;
NP=FCO2D1*NP_CO2    +FCOD1*NP_CO  +FCH4D1*NP_CH4  +FN2OD1*NP_N2O
+FNOxD1*NP_NOx  +FSO2D1*NP_SO2  +FHCD1*NP_HC  +FR134AD1*NP_R;
ATP=FCO2D1*ATP_CO2  +FCOD1*ATP_CO +FCH4D1*ATP_CH4 +FN2OD1*ATP_N2O
+FNOxD1*ATP_NOx +FSO2D1*ATP_SO2 +FHCD1*ATP_HC +FR134AD1*ATP_R;
ADP=2*OPD*(B11*Trip_req_M1*D1*Fuel_consM1+B12*Trip_req_M2*D1*Fuel_con
sM2+B13*Trip_req_M3*D1*Fuel_consM3+B14*Trip_req_M4*D1*Fuel_consM4)*AD
P_Fuel;


!Social, HTPE:human toxicity potential, Risk: Transportation risk;

HTPE=FCO2D1*HTPE_CO2  +FCOD1*HTPE_CO +FCH4D1*HTPE_CH4+FN2OD1*HTPE_N2O
+FNOxD1*HTPE_NOx +FSO2D1*HTPE_SO2 +FHCD1*HTPE_HC+FR134AD1*HTPE_R;
```

```
Risk_M1=0.3203; Risk_M2=0.8152; Risk_M3=0.9697;
Risk_M4=0.9998;Risk=B11*Trip_req_M1*Risk_M1+B12*Trip_req_M2*Risk_M2+B
13*Trip_req_M3*Risk_M3+B14*Trip_req_M4*Risk_M4;

!Weighted sum approach;
!degree of satisfaction;
!lamda_macro=w_EC*lamda_EC+w_EN*lamda_EN;
!lamda_EC=(22085.02-C_Tr)/(22085.02-14650.11);
!lamda_EN=w_GWP*lamda_GWP+w_AP*lamda_AP+w_POCP*lamda_POCP+w_NP*lamda_
NP;
!lamda_GWP=(4373.419-GWP)/(4373.419-2428.643);
!lamda_AP=(8.35746-AP)/(8.35746-4.640828);
!lamda_POCP=(21.1128-POCP)/(21.1128-11.72434);
!lamda_NP=(0.956117-NP)/(9.56117-0.53095);
w_GWP=0.2; w_AP=0.2; w_POCP=0.2; w_NP=0.2; w_ATP=0.2;
w_EC=0.67; w_EN=0.33;

end
```

A.4.3 Lingo code for technology selection (with max-min aggregation approach and weighted sum approach)

```
!max=lamda;
max=lamda_micro;
!max=JC;!min=ISI;!min=HTPE;!max=C_GP;!max=GWP;!min=Fwater;
!max=AP;!min=ADP;!min=TTP;!max=ATP;!max=NP;!max=POCP;!OPH=8640h/y;
!Input biomass, PD:paddy, RH:rice husk, RS:rice straw, SC:sugarcane,
BG:bagasse, PA: pineapple, PAW:peel, PO:palm oil, EFB:empty fruit
branch, PKS:palm kernel shell;
FPD=1.6426; ![t/h];
FRH=FPD*0.22;FRS=FPD*0.28;
FRH=FRH_PyF+FRH_PyS+FRH_Combust;
FRS=FRS_Combust+FRS_Cond;
@bin(B1);@bin(B2);@bin(B3);@bin(B4);@bin(B5);
B1+B2+B3=1;B4+B5=1;
M=1000000;
FRH_PyF<=B1*M;FRH_PyS<=B2*M;FRH_Combust<=B3*M;
FRS_Combust<=B4*M;FRS_Cond<=B5*M;
FSC=1.3309; !t/h;
FBG=FSC*0.28;
FBG=FBG_DAcFer+FBG_DAlFer+FBG_HWFer+FBG_SEFer+FBG_Combust;
@bin(B6);@bin(B7);@bin(B8);@bin(B9);@bin(B10);
B6+B7+B8+B9+B10=1;
FBG_DAcFer<=B6*M;FBG_DAlFer<=B7*M;FBG_HWFer<=B8*M;
FBG_SEFer<=B9*M;FBG_Combust<=B10*M;
FPA=0.7249; !t/h;
FPAW=FPA*0.2;
FPAW=FPAW_AD+FPAW_Drying+FPAW_Fer;
@bin(B11);@bin(B12);@bin(B13);
B11+B12+B13=1;
FPAW_AD<=B11*M;FPAW_Drying<=B12*M;FPAW_Fer<=B13*M;
FOP=1000; ![t/h];
FEFB=FOP*0.234;FPKS=FOP*0.073;
FEFB=FEFB_DLFPrd+FEFB_G+FEFB_Combust;
FPKS=FPKS_Briq+FPKS_Combust;
@bin(B14);@bin(B15);@bin(B16);@bin(B17);@bin(B18);
B14+B15+B16=1;B17+B18=1;
FEFB_DLFPrd<=B14*M;FEFB_G<=B15*M;FEFB_Combust<=B16*M;
FPKS_Briq<=B17*M;FPKS_Combust<=B18*M;
```

```
!Conversion;
X_oilF=500;        X_oilS=299;!L/t;
X_charF=0.15;      X_charS=0.35;!t/t;
X_syngasF=0.208;   X_syngasS=0.315;!m3/t;
X_Cond=0.7; ![t/t];
X_ethanolDAc=252.6;           X_ethanolDAl=255.8;
X_ethanolHW=255.3;            X_ethanolSE=230.2;   !L/t;
X_Biogas=55;!m3/t;
X_BiogasElec=6;!kWh/m3;
X_AFeed=0.6;!t/t;
X_CitricA=0.194;!t/t;
X_DLF=0.3752;           X_EP=0.33;!t/t;
X_SyngasG=0.427;![m3/t];  X_OilG=299;![L/t];   X_CharG=0.20; ![t/t];
X_RSCombust=4.79;![tHPS/t];
X_RHCombust=5.99;![tHPS/t];
X_BGCombust=2.2;![tHPS/t];
X_CombustElec=0.58; ![kW/t/h];
X_EFBCombust=2.59;![tHPS/t];
X_PKSCombust=3.96;![tHPS/t];
Foil   = FRH_PyF*X_oilF    +FRH_PyS*X_oilS    +FEFB_G*X_OilG;
Fchar  = FRH_PyF*X_charF   +FRH_PyS*X_charS   +FEFB_G*X_CharG;
Fsyngas= FRH_PyF*X_syngasF +FRH_PyS*X_syngasS;
FAFeed= FRS_Cond*X_Cond+FPAW_Drying*X_AFeed;
FEthanol=FBG_DAcFer*X_ethanolDAc+FBG_DAlFer*X_ethanolDAl+FBG_HWFer*X_
ethanolHW+FBG_SEFer*X_ethanolSE;
FCitricA=FPAW_Fer*X_CitricA;
FDLF=FEFB_DLFPrd*X_DLF;
FEP=FPKS_Briq*X_EP;
FsyngasG=FEFB_G*X_SyngasG;

!Generated power;
ElecGen=(FRS_Combust*X_RSCombust+FRH_Combust*X_RHCombust+FEFB_Combust
*X_EFBCombust+FPKS_Combust*X_PKSCombust+FBG_Combust*X_BGCombust)*X_Co
mbustElec+FPAW_AD*X_Biogas*X_BiogasElec;

!Elec requirement [kW/t/h];
Y_ElecPyF=180;    Y_ElecPyS=150;  Y_ElecCond=30;
Y_ElecDAcFer=58.19;     Y_ElecDAlFer=62.46;
Y_ElecHWFer=57.48;      Y_ElecSEFer=36.14;
Y_ElecFer=81.25;  Y_ElecDry=30;   Y_ElecAD=35;
Y_ElecDLF=220;    Y_ElecEP=140;   Y_ElecG=280;
Y_ElecCombust=0;
ElecReq=FRH_PyF*Y_ElecPyF+FRH_PyS*Y_ElecPyS+FRS_Cond*Y_ElecCond+FBG_D
AcFer*Y_ElecDAcFer+FBG_DAlFer*Y_ElecDAlFer+FBG_HWFer*Y_ElecHWFer+FBG_
SEFer*Y_ElecSEFer+FPAW_AD*Y_ElecAD+FPAW_Drying*Y_ElecDry+FPAW_Fer*Y_E
lecFer+FEFB_DLFPrd*Y_ElecDLF+FPKS_Briq*Y_ElecEP+FEFB_G*Y_ElecG+(FRS_C
ombust+FRH_Combust+FEFB_Combust+FPKS_Combust+FBG_Combust)*Y_ElecCombu
st;
ElecImp+ElecGen=ElecReq+ElecExp;
ElecImp=@if(ElecReq #LT# ElecGen,0,ElecReq-ElecGen);

!Economic data;
CF_RH= 90; CF_RS= 58.5; CF_BG= 10; CF_PAW= 10; CF_EFB=10.8; CF_PKS=
12.6; ![RM/t];
CF_oil=1.1;![RM/L];CF_char=1260;![RM/t];
CF_syngas=600; ![RM/m3];CF_AFeed=260; ![RM/t];
CF_Ethanol=3.04;![RM/L];CF_CitricA=2520;![RM/t];
CF_DLF=720;![RM/t];CF_EP=600;![RM/t];
CF_SyngasG=400;![RM/m3];CF_ElecImp= 0.55;![RM/kWh];
CF_ElecExp= 0.43;![RM/kWh];
```

```
CF_PyF=312; CF_PyS=281; CF_CombustRS=46.03;
CF_Cond=60;CF_CombustRH=56.54; ![RM/t/h];
CF_DAcFer=445; CF_DAlFer=419; CF_HWFer=413.6; CF_SEFer=372;
CF_CombustBG=81.1;
CF_Fer=320; CF_Drying=60; CF_AD=375;
CF_DLFPrd=99; CF_Briq=93.6; CF_G=330; CF_CombustEFB=24.87;
CF_CombustPKS=38.05;

!Economic Performance;
C_GP=(Foil*CF_oil+Fchar*CF_char+Fsyngas*CF_syngas+FAFeed*CF_AFeed+FEt
hanol*CF_Ethanol+FCitricA*CF_CitricA+FDLF*CF_DLF+FEP*CF_EP+FsyngasG*C
F_SyngasG+ElecExp*CF_ElecExp-ElecImp*CF_ElecImp-FRH*CF_RH-FRS*CF_RS-
FRH_PyF*CF_PyF-FRH_PyS*CF_PyS-FRS_Cond*CF_Cond-FBG*CF_BG-
FBG_DAcFer*CF_DAcFer-FBG_DAlFer*CF_DAlFer-FBG_HWFer*CF_HWFer-
FBG_SEFer*CF_SEFer-FPAW*CF_PAW-FPAW_AD*CF_AD-FPAW_Drying*CF_Drying-
FPAW_Fer*CF_Fer-FEFB*CF_EFB-FPKS*CF_PKS-FEFB_DLFPrd*CF_DLFPrd-
FPKS_Briq*CF_Briq-FEFB_G*CF_G-FRS_Combust*CF_CombustRS-
FRH_Combust*CF_CombustRH-FBG_Combust*CF_CombustBG-
FEFB_Combust*CF_CombustEFB-FPKS_Combust*CF_CombustPKS);![RM/h];
@free(C_GP);

!Environmental data;
X_CO2F=463;   X_CO2S=404;
X_COF=0.058;  X_COS=0.0549;
X_CH4F=0.003; X_CH4S=0.0037;
X_CO2DAcFer=1126;    X_CO2DAlFer=1205;  X_CO2HWFer=1154;
X_CO2SEFer=865.6;
X_CODAcFer=0.305;    X_CODAlFer=0.316;  X_COHWFer=0.324;
X_COSEFer=0.218;
X_CH4DAcFer=1.124;   X_CH4DAlFer=1.132; X_CH4HWFer=0.121;
X_CH4SEFer=1.1;
X_CO2Fer=300;    X_COFer=0.081;     X_CH4Fer=0.03;
!X_CO2AD=970;    !X_COAD=0.471;     !X_CH4AD=23;  ![g/kg];
X_CO2AD=0;    X_COAD=0;  X_CH4AD=0;
X_N2OAD=0.003;![g/kg];
X_CO2DLF=0; X_CO2EP=0; X_CO2G=588.6;
X_CODLF=0;  X_COEP=0;  X_COG=0.0803;
X_CH4DLF=0; X_CH4EP=0; X_CH4G=0.0054;
!X_CO2Combust=1585;
!X_COCombust=102;
!X_CH4Combust=5.82;  ![g/kg];
X_CO2Combust=0;X_COCombust=0;X_CH4Combust=0;  ![g/kg];
FCO2=FRH_PyF*X_CO2F+FRH_PyS*X_CO2S+FBG_DAcFer*X_CO2DAcFer+FBG_DAlFer*
X_CO2DAlFer+FBG_HWFer*X_CO2HWFer+FBG_SEFer*X_CO2SEFer+FPAW_AD*X_CO2AD
+FPAW_Fer*X_CO2Fer+FEFB_DLFPrd*X_CO2DLF+FPKS_Briq*X_CO2EP+FEFB_G*X_CO
2G+(FRS_Combust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_
CO2Combust;
FCO=FRH_PyF*X_COF+FRH_PyS*X_COS+FBG_DAcFer*X_CODAcFer+FBG_DAlFer*X_CO
DAlFer+FBG_HWFer*X_COHWFer+FBG_SEFer*X_COSEFer+FPAW_AD*X_COAD+FPAW_Fe
r*X_COFer+FEFB_DLFPrd*X_CODLF+FPKS_Briq*X_COEP+FEFB_G*X_COG+(FRS_Comb
ust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_COCombust;
FCH4=FRH_PyF*X_CH4F+FRH_PyS*X_CH4S+FBG_DAcFer*X_CH4DAcFer+FBG_DAlFer*
X_CH4DAlFer+FBG_HWFer*X_CH4HWFer+FBG_SEFer*X_CH4SEFer+FPAW_AD*X_CH4AD
+FPAW_Fer*X_CH4Fer+FEFB_DLFPrd*X_CH4DLF+FPKS_Briq*X_CH4EP+FEFB_G*X_CH
4G+(FRS_Combust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_
CH4Combust;
FN2O=FPAW_AD*X_N2OAD;  ![kg/h];
X_NOxF=0.0553;   X_NOxS=0.0549;
X_SO2F=0.0030;   X_SO2S=0.0037;
X_HCF=0.0030;    X_HCS=0.0037;
X_NOxDAcFer=0.305;X_NOxDAlFer=0.312;
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X_NOxHWFer=0.324;X_NOxSEFer=0.218;
X_SO2DAcFer=0.775;    X_SO2DAlFer=0.675;
X_SO2HWFer=0.513;    X_SO2SEFer=0.796;
X_HCDAcFer=0;         X_HCDAlFer=0;
X_HCHWFer=0;         X_HCSEFer=0;
X_NOxFer=0.08;   X_SO2Fer=0.121; X_HCFer=0;
X_NOxAD=0; !X_NOxAD=0.561;    X_SO2AD=0.121;
X_HCAD=0.4709;  ![g/kg];
X_NOxDLF=0;   X_NOxEP=0; X_NOxG=0.0803;
X_SO2DLF=0;   X_SO2EP=0; X_SO2G=0.0054;
X_HCDLF=0;    X_HCEP=0;  X_HCG=0.0054;
!X_NOxCombust=3.11;
X_NOxCombust=0;    X_SO2Combust=0;  X_HCCombust=25.406;  ![g/kg];
FNOX=FRH_PyF*X_NOXF+FRH_PyS*X_NOXS+FBG_DAcFer*X_NOXDAcFer+FBG_DAlFer*
X_NOXDAlFer+FBG_HWFer*X_NOXHWFer+FBG_SEFer*X_NOXSEFer+FPAW_AD*X_NOXAD
+FPAW_Fer*X_NOXFer+FEFB_DLFPrd*X_NOXDLF+FPKS_Briq*X_NOXEP+FEFB_G*X_NO
XG+(FRS_Combust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_
NOXCombust;
FSO2=FRH_PyF*X_SO2F+FRH_PyS*X_SO2S+FBG_DAcFer*X_SO2DAcFer+FBG_DAlFer*
X_SO2DAlFer+FBG_HWFer*X_SO2HWFer+FBG_SEFer*X_SO2SEFer+FPAW_AD*X_SO2AD
+FPAW_Fer*X_SO2Fer+FEFB_DLFPrd*X_SO2DLF+FPKS_Briq*X_SO2EP+FEFB_G*X_SO
2G+(FRS_Combust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_
SO2Combust;
FHC=FRH_PyF*X_HCF+FRH_PyS*X_HCS+FBG_DAcFer*X_HCDAcFer+FBG_DAlFer*X_HC
DAlFer+FBG_HWFer*X_HCHWFer+FBG_SEFer*X_HCSEFer+FPAW_AD*X_HCAD+FPAW_Fe
r*X_HCFer+FEFB_DLFPrd*X_HCDLF+FPKS_Briq*X_HCEP+FEFB_G*X_HCG+(FRS_Comb
ust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_HCCombust;
X_CODF=60;   X_CODS=60;
X_CODDAcFer=252.6;    X_CODDAlFer=255.8;  X_CODHWFer=255.3;
X_CODSEFer=230.2;
X_CODFer=263;    X_CODAD=-2.522;
X_CODDLF=60;   X_CODEP=0;  X_CODG=60;
X_CODCombust=0.02;  ![g/kg];
FCOD=FRH_PyF*X_CODF+FRH_PyS*X_CODS+FBG_DAcFer*X_CODDAcFer+FBG_DAlFer*
X_CODDAlFer+FBG_HWFer*X_CODHWFer+FBG_SEFer*X_CODSEFer+FPAW_AD*X_CODAD
+FPAW_Fer*X_CODFer+FEFB_DLFPrd*X_CODDLF+FPKS_Briq*X_CODEP+FEFB_G*X_CO
DG+(FRS_Combust+FRH_Combust+FBG_Combust+FEFB_Combust+FPKS_Combust)*X_
CODCombust;
@free(X_CODAD);
@free(FCOD);
Y_WaterPyF=0.0231;    Y_WaterPyS=0.0231; ![m3/t];
Y_WaterDAcFer=0.1489; Y_WaterDAlFer=0.1510; Y_WaterHWFer=0.1685;
Y_WaterSEFer=0.1154;![m3/t];
Y_WaterFer=0.0214;    Y_WaterAD= 0; ![m3/t];
Y_WaterDLF=0;         Y_WaterEP=0;          Y_WaterG=0.138;![m3/t];
Y_WaterCombust= 1.8*10^-5; ![m3/kWh];
FWATER=FRH_PyF*Y_WaterPyF+FRH_PyS*Y_WaterPyS+FBG_DAcFer*Y_WaterDAcFer
+FBG_DAlFer*Y_WaterDAlFer+FBG_HWFer*Y_WaterHWFer+FBG_SEFer*Y_WaterSEF
er+FEFB_DLFPrd*Y_WaterDLF+FPKS_Briq*Y_WaterEP+FEFB_G*Y_WaterG+FPAW_AD
*Y_WaterAD+FPAW_Fer*Y_WaterFer+(FRS_Combust+FRH_Combust+FBG_Combust+F
EFB_Combust+FPKS_Combust)*Y_WaterCombust;![m3/h];

!PEI (WAR), GWP:global warming potential, AP: acidification
potential, POCP: photochemical ozone creation potential, NP:
neutrification potential, ATP:aquatic toxicity potential, TTP:
terrestrial toxicity potential, ADP: abiotic depletion potential,
HTPE,HTPI:human toxicity potential;
GWP_CO2=1;AP_CO2=0;POCP_CO2=0;NP_CO2=0;ATP_CO2=0;TTP_CO2=0;ADP_CO2=0;
HTPE_CO2=0.0001;
GWP_CO=0;AP_CO=0;POCP_CO=0.01470;NP_CO=0;ATP_CO=0;TTP_CO=0;ADP_CO=0;
HTPE_CO=0.0182;
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GWP_CH4=23;AP_CH4=0;POCP_CH4=0.00384;NP_CH4=0;ATP_CH4=0;TTP_CH4=0;
ADP_CH4=0;HTPE_CH4=0.0015;
GWP_NOx=0;AP_NOX=1.1;POCP_NOx=1.3;NP_NOx=0.13;ATP_NOx=0;TTP_NOx=0;
ADP_NOx=0;HTPE_NOx=0;
GWP_N2O=296;AP_N2O=0.7;POCP_N2O=0.00384;NP_N2O=0;ATP_N2O=0;TTP_N2O=0;
ADP_N2O=0;HTPE_N2O=0.0111;
GWP_SO2=0;AP_SO2=1;POCP_SO2=0.125;NP_SO2=0;ATP_SO2=0;TTP_SO2=0;
ADP_SO2=0;HTPE_SO2=0.0769;
GWP_HC=0;AP_HC=0.018;POCP_HC=0.416;NP_HC=0;ATP_HC=0;TTP_HC=0;
ADP_HC=0;HTPE_HC=0;
GWP_COD=0;AP_COD=0;POCP_COD=0;NP_COD=0.022;ATP_COD=0;TTP_COD=0;
ADP_COD=0;HTPE_COD=0;![kg-eq/kg];
GWP_Coal=23.02;AP_Coal=0.177;POCP_Coal=0;NP_Coal=0;ATP_Coal=2.081*10^
-5;  TTP_Coal=6.071*10^-6; ADP_Coal=0.0134;HTPE_Coal=0;
GWP_Oil=0;AP_Oil=0;POCP_Oil=0.923;NP_Oil=0;ATP_Oil=0.16393;TTP_Oil=0.
00204;ADP_Oil=0;HTPE_Oil=0.2;
GWP_Char=0;AP_Char=0;POCP_Char=0;NP_Char=0.5037;ATP_Char=8.4238;
TTP_Char=0.1687;ADP_Char=0;HTPE_Char=0;
GWP_SyngasF=9.156;AP_SyngasF=0;POCP_SyngasF=0.0636;NP_SyngasF=0;
ATP_SyngasF=0;TTP_SyngasF=0;ADP_SyngasF=0;HTPE_SyngasF=0.00463;
GWP_SyngasS=9.107; AP_SyngasS=0;POCP_SyngasS=0.0353;NP_SyngasS=0;
ATP_SyngasS=0;TTP_SyngasS=0;ADP_SyngasS=0;HTPE_SyngasS=0.00461;
GWP_AFeed=0;AP_AFeed=0;POCP_AFeed=0;NP_AFeed=0.503;ATP_AFeed=0;
TTP_AFeed=0;ADP_AFeed=0;HTPE_Afeed=0;
GWP_Ethanol=0;AP_Ethanol=0;POCP_Ethanol=0.407;NP_Ethanol=0;ATP_Ethano
l=0.00007;TTP_Ethanol=0.00011;ADP_Ethanol=0;HTPE_Ethanol=0.0001;
GWP_CitricA=0;AP_CitricA=0;POCP_CitricA=0.407;NP_CitricA=0;ATP_Citric
A=0.00361;TTP_CitricA=0.00015;ADP_CitricA=0;HTPE_CitricA=0;
GWP_DLF=0;AP_DLF=0;POCP_DLF=0;NP_DLF=0;ATP_DLF=0;TTP_DLF=0;ADP_DLF=0;
HTPE_DLF=0;
GWP_EP=0;AP_EP=0;POCP_EP=0.923;NP_EP=0;ATP_EP=0.16393;TTP_EP=0.00204;
ADP_EP=0;HTPE_EP=0.2;
GWP_SyngasG=0.6248;AP_SyngasG=0;POCP_SyngasG=0.0038;NP_SyngasG=0;
ATP_SyngasG=0;TTP_SyngasG=0;ADP_SyngasG=0;HTPE_SyngasG=0.00481;

!Environmental performance;
FCoal=ElecImp/8.141;
!FCoal_Sub=ElecGen/8.141;
FCoal_Sub=ElecGen/8.141+(Foil*21.6+FRH_PyF*X_syngasF*19.566
+FRH_PyS*X_syngasS*20.286+FEthanol*21+FEP*21*1000+FsyngasG*10.935)/29
.308;
FCoal_Sub_Elec=ElecGen/8.141;
!Biooil-to-power:21.6MJ/L;
!Syngas-to-power:19.566MJ/m3 (fast) 20.286/mj/m3 (slow);
!Coal-to-power:29.308 MJ/kg or 8.141 kWh/kg;

GWP= (FCO2*GWP_CO2 +FCO*GWP_CO+FCH4*GWP_CH4+FN2O*GWP_N2O+FNOx*GWP_NOx
+FSO2*GWP_SO2+FHC*GWP_HC+FCOD*GWP_COD+FOil*1.17*GWP_Oil+FChar*1000*GW
P_Char+FRH_PyF*X_syngasF*0.95*GWP_SyngasF+FRH_PyS*X_syngasS*0.95*GWP_
SyngasS+FAFeed*1000*GWP_AFeed+FEthanol*0.789*GWP_Ethanol+FCitricA*GWP
_CitricA*1000+FDLF*1000*GWP_DLF+FEP*1000*GWP_EP+FsyngasG*0.95*GWP_syn
gasG +(FCoal-FCoal_Sub)*GWP_Coal);

AP=(FCO2*AP_CO2  +FCO*AP_CO  +FCH4*AP_CH4  +FN2O*AP_N2O  +FNOx*AP_NOx
+FSO2*AP_SO2+FHC*AP_HC+FCOD*AP_COD+FOil*1.17*AP_Oil+FChar*1000*AP_Cha
r+FRH_PyF*X_syngasF*0.95*AP_SyngasF+FRH_PyS*X_syngasS*0.95*AP_SyngasS
+FAFeed*1000*AP_AFeed+FEthanol*0.789*AP_Ethanol+FCitricA*AP_CitricA*1
000  +FDLF*1000*AP_DLF+FEP*1000*AP_EP+FsyngasG*0.95*AP_syngasG
+(FCoal-FCoal_Sub)*AP_Coal);
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POCP=(FCO2*POCP_CO2+FCO*POCP_CO+FCH4*POCP_CH4+FN2O*POCP_N2O+FNOx*POCP
_NOx+FSO2*POCP_SO2+FHC*POCP_HC+FCOD*POCP_COD+FOil*1.17*POCP_Oil+FChar
*1000*POCP_Char+FRH_PyF*X_syngasF*0.95*POCP_SyngasF+FRH_PyS*X_syngasS
*0.95*POCP_SyngasS+FAFeed*1000*POCP_AFeed+FEthanol*0.789*POCP_Ethanol
+FCitricA*POCP_CitricA*1000+FDLF*1000*POCP_DLF+FEP*1000*POCP_EP+Fsyng
asG*0.95*POCP_syngasG+(FCoal-FCoal_Sub)*POCP_Coal);

NP= (FCO2*NP_CO2  +FCO*NP_CO  +FCH4*NP_CH4  +FN2O*NP_N2O+FNOx*NP_NOx
+FSO2*NP_SO2+FHC*NP_HC+FCOD*NP_COD+FOil*1.17*NP_Oil+FChar*1000*NP_Cha
r+FRH_PyF*X_syngasF*0.95*NP_SyngasF+FRH_PyS*X_syngasS*0.95*NP_SyngasS
+FAFeed*1000*NP_AFeed+FEthanol*0.789*NP_Ethanol+FCitricA*NP_CitricA*1
000+FDLF*1000*NP_DLF+FEP*1000*NP_EP+FsyngasG*0.95*NP_syngasG+(FCoal-
FCoal_Sub)*NP_Coal);

ATP= (FCO2*ATP_CO2 +FCO*ATP_CO+FCH4*ATP_CH4+FN2O*ATP_N2O+FNOx*ATP_NOx
+FSO2*ATP_SO2+FHC*ATP_HC+FCOD*ATP_COD+FOil*1.17*ATP_Oil+FChar*1000*AT
P_Char+FRH_PyF*X_syngasF*0.95*ATP_SyngasF+FRH_PyS*X_syngasS*0.95*ATP_
SyngasS+FAFeed*1000*ATP_AFeed+FEthanol*0.789*ATP_Ethanol+FCitricA*ATP
_CitricA*1000+FDLF*1000*ATP_DLF+FEP*1000*ATP_EP+FsyngasG*0.95*ATP_syn
gasG +(FCoal-FCoal_Sub)*ATP_Coal);

TTP= (FCO2*TTP_CO2 +FCO*TTP_CO+FCH4*TTP_CH4+FN2O*TTP_N2O+FNOx*TTP_NOx
+FSO2*TTP_SO2+FHC*TTP_HC+FCOD*TTP_COD+FOil*1.17*TTP_Oil+FChar*1000*TT
P_Char+FRH_PyF*X_syngasF*0.95*TTP_SyngasF+FRH_PyS*X_syngasS*0.95*TTP_
SyngasS+FAFeed*1000*TTP_AFeed+FEthanol*0.789*TTP_Ethanol+FCitricA*TTP
_CitricA*1000+FDLF*1000*TTP_DLF+FEP*1000*TTP_EP+FsyngasG*0.95*TTP_syn
gasG +(FCoal-FCoal_Sub)*TTP_Coal);

ADP= (FCO2*ADP_CO2 +FCO*ADP_CO+FCH4*ADP_CH4+FN2O*ADP_N2O+FNOx*ADP_NOx
+FSO2*ADP_SO2+FHC*ADP_HC+FCOD*ADP_COD+FOil*1.17*ADP_Oil+FChar*1000*AD
P_Char+FRH_PyF*X_syngasF*0.95*ADP_SyngasF+FRH_PyS*X_syngasS*0.95*ADP_
SyngasS+FAFeed*1000*ADP_AFeed+FEthanol*0.789*ADP_Ethanol+FCitricA*ADP
_CitricA*1000+FDLF*1000*ADP_DLF+FEP*1000*ADP_EP+FsyngasG*0.95*ADP_syn
gasG +(FCoal-FCoal_Sub)*ADP_Coal);

!Social data;
!ISI score;
ISI_DLF=12; ISI_EP=13; ISI_G=34; ISI_PyF=31; ISI_PyS=30;
ISI_DAcFer=22; ISI_DAlFer=22; ISI_HWFer=24; ISI_SEFer=26;
ISI_Citric=25; ISI_AD=30; ISI_AFeed=9; ISI_Fertiliser=15;
ISI_Combust=35;

ISI=FEFB_DLFPrd/FEFB*ISI_DLF+FPKS_Briq/FPKS*ISI_EP+FEFB_G/FEFB*ISI_G+
FRH_PyF/FRH*ISI_PyF+FRH_PyS/FRH*ISI_PyS+FBG_DAcFer/FBG*ISI_DAcFer+FBG
_DAlFer/FBG*ISI_DAlFer+FBG_HWFer/FBG*ISI_HWFer+FBG_SEFer/FBG*ISI_SEFe
r+FPAW_Fer/FPaw*ISI_Citric+FPAW_AD/FPaw*ISI_AD+FPAW_Drying/FPaw*ISI_A
Feed+FRS_Cond/FRS*ISI_Fertiliser+(FRH_Combust/FRH+FRS_Combust/FRS+FBG
_Combust/FBG+FEFB_Combust/FEFB+FPKS_Combust/FPKS)*ISI_Combust;

!Human Toxicity;
HTPE=(FCO2*HTPE_CO2+FCO*HTPE_CO+FCH4*HTPE_CH4+FN2O*HTPE_N2O+FNOx*HTPE
_NOx+FSO2*HTPE_SO2+FHC*HTPE_HC+FCOD*HTPE_COD+FOil*1.17*HTPE_Oil+FChar
*1000*HTPE_Char+FRH_PyF*X_syngasF*0.95*HTPE_SyngasF+FRH_PyS*X_syngasS
*0.95*HTPE_SyngasS+FAFeed*1000*HTPE_AFeed+FEthanol*0.789*HTPE_Ethanol
+FCitricA*HTPE_CitricA*1000+FDLF*1000*HTPE_DLF+FEP*1000*HTPE_EP+Fsyng
asG*0.95*HTPE_syngasG+(FCoal-FCoal_Sub)*HTPE_Coal);

HTPI=TTP;
!Job;
JC_DLF=0.002; JC_EP=0.0215;JC_GasPy=0.004; JC_Ethanol=0.01;
JC_Citric=0.005; JC_AD=2.21; JC_AFeed=0.0004; JC_Combust=0.576;
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JC=FDLF*JC_DLF+FEP*JC_EP+Foil*JC_GasPy+FEthanol*JC_Ethanol+FCitricA*J
C_Citric+FPAW_AD*X_Biogas*X_BiogasElec/1000*JC_AD+FAFeed*JC_AFeed+(FR
S_Combust*X_RSCombust+FRH_Combust*X_RHCombust+FEFB_Combust*X_EFBCombu
st+FPKS_Combust*X_PKSCombust+FBG_Combust*X_BGCombust)*X_CombustElec/1
000*JC_Combust;
@free(GWP);@free(AP);@free(POCP);@free(NP);@free(ATP);@free(TTP);@fre
e(ADP);@free(HTPI);@free(HTPE);

!Sustainability measurement;
!Weighted sum approach;
lamda_micro=w_EC*lamda_EC+w_EN*lamda_EN+w_SC*lamda_SC;
lamda_EC=@if(C_GP#LT#0,0,C_GP/61535.4);
lamda_EN=w_GWP*lamda_GWP+w_AP*lamda_AP+w_POCP*lamda_POCP+w_NP*lamda_N
P+w_ATP*lamda_ATP+w_TTP*lamda_TTP+w_ADP*lamda_ADP+w_water*lamda_water
;
lamda_SC=w_HTPI*lamda_HTPI+w_HTPE*lamda_HTPE+w_Job*lamda_Job+w_ISI*la
mda_ISI;
!lamda_micro=w_EC*lamda_EC+w_EN*lamda_EN;

!degree of satisfaction for each impact;
lamda_GWP=(144727-GWP)/(144727-(-1237304));
lamda_AP=(1146.21-AP)/(1146.21-(-10555.36));
lamda_POCP=(98060.1-POCP)/(98060.1);
lamda_NP=(24156.52-NP)/(24156.52);
lamda_ATP=(412687.4-ATP)/(412687.4-(-0.00146));
lamda_TTP=(8132.55-TTP)/(8132.55-(-0.00043));
lamda_ADP=(84.22-ADP)/(84.22-(-800.812));
lamda_water=(32.368-FWater)/(32.368);
lamda_HTPI=lamda_TTP;
lamda_HTPE=(21247.1-HTPE)/(21247.1);
lamda_ISI=(205-ISI)/(205-101);
lamda_Job=(JC)/(282.1645);
!Fuzzy approach;
lamda<lamda_EC;
lamda<lamda_EN;
lamda<lamda_SC;

!relative importance, exte=racted from AHP results;
w_GWP=1/8;w_AP=1/8;w_POCP=1/8;w_NP=1/8;
w_ATP=1/8;w_TTP=1/8;w_ADP=1/8;w_water=1/8;
w_HTPI=1/4;w_HTPE=1/4;w_ISI=1/4;w_Job=1/4;
w_EC=0.5;w_EN=0.25;w_SC=0.25;

end
```

A.4.3 Optimised solution (technology selection)

```
  Global optimal solution found.
  Objective value:                              0.7053632
  Objective bound:                              0.7053632
  Infeasibilities:                               0.000000
  Extended solver steps:                                0
  Total solver iterations:                             24
  Elapsed runtime seconds:                           3.28

  Model Class:                                      MINLP

  Total variables:                90
```

```
Nonlinear variables:                3
Integer variables:                 18

Total constraints:                 87
Nonlinear constraints:              2

Total nonzeros:                   408
Nonlinear nonzeros:                 3
```

Variable	Value	Reduced Cost
LAMDA_MICRO	0.7053632	0.000000
FPD	1.642600	0.000000
FRH	0.3613720	0.000000
FRS	0.4599280	0.000000
FRH_PYF	0.000000	0.000000
FRH_PYS	0.3613720	-0.2002345E-02
FRH_COMBUST	0.000000	0.1042854E-01
FRS_COMBUST	0.000000	0.2669950E-01
FRS_COND	0.4599280	0.000000
B1	0.000000	0.000000
B2	1.000000	0.000000
B3	0.000000	0.000000
B4	0.000000	0.000000
B5	1.000000	0.000000
M	1000000.	0.000000
FSC	1.330900	0.000000
FBG	0.3726520	0.000000
FBG_DACFER	0.000000	0.000000
FBG_DALFER	0.3726520	-0.2769079E-03
FBG_HWFER	0.000000	0.2910066E-02
FBG_SEFER	0.000000	0.6339912E-02
FBG_COMBUST	0.000000	0.2450374E-01
B6	0.000000	0.000000
B7	1.000000	0.000000
B8	0.000000	0.000000
B9	0.000000	0.000000
B10	0.000000	0.000000
FPA	0.7249000	0.000000
FPAW	0.1449800	0.000000
FPAW_AD	0.000000	0.000000
FPAW_DRYING	0.1449800	-0.6563887E-01
FPAW_FER	0.000000	0.000000
B11	0.000000	0.000000
B12	1.000000	0.000000
B13	0.000000	0.000000
FOP	1000.000	0.000000
FEFB	234.0000	0.000000
FPKS	73.00000	0.000000
FEFB_DLFPRD	0.000000	0.000000
FEFB_G	234.0000	-0.1173395E-02
FEFB_COMBUST	0.000000	0.5193612E-03
FPKS_BRIQ	73.00000	-0.5652968E-03
FPKS_COMBUST	0.000000	0.000000
B14	0.000000	0.000000
B15	1.000000	0.000000
B16	0.000000	0.000000
B17	1.000000	0.000000
B18	0.000000	0.000000
X_OILF	500.0000	0.000000

X_OILS	299.0000	0.000000
X_CHARF	0.1500000	0.000000
X_CHARS	0.3500000	0.000000
X_SYNGASF	0.2080000	0.000000
X_SYNGASS	0.3150000	0.000000
X_COND	0.7000000	0.000000
X_ETHANOLDAC	252.6000	0.000000
X_ETHANOLDAL	255.8000	0.000000
X_ETHANOLHW	255.3000	0.000000
X_ETHANOLSE	230.2000	0.000000
X_BIOGAS	55.00000	0.000000
X_BIOGASELEC	6.000000	0.000000
X_AFEED	0.6000000	0.000000
X_CITRICA	0.1940000	0.000000
X_DLF	0.3752000	0.000000
X_EP	0.3300000	0.000000
X_SYNGASG	0.4270000	0.000000
X_OILG	299.0000	0.000000
X_CHARG	0.2000000	0.000000
X_RSCOMBUST	4.790000	0.000000
X_RHCOMBUST	5.990000	0.000000
X_BGCOMBUST	2.200000	0.000000
X_COMBUSTELEC	0.5800000	0.000000
X_EFBCOMBUST	2.590000	0.000000
X_PKSCOMBUST	3.960000	0.000000
FOIL	70074.05	0.000000
FCHAR	46.92648	0.000000
FSYNGAS	0.1138322	0.000000
FAFEED	0.4089376	0.000000
FETHANOL	95.32438	0.000000
FCITRICA	0.000000	0.000000
FDLF	0.000000	0.000000
FEP	24.09000	0.000000
FSYNGASG	99.91800	0.000000
ELECGEN	0.000000	0.7004270E-04
Y_ELECPYF	180.0000	0.000000
Y_ELECPYS	150.0000	0.000000
Y_ELECCOND	30.00000	0.000000
Y_ELECDACFER	58.19000	0.000000
Y_ELECDALFER	62.46000	0.000000
Y_ELECHWFER	57.48000	0.000000
Y_ELECSEFER	36.14000	0.000000
Y_ELECFER	81.25000	0.000000
Y_ELECDRY	30.00000	0.000000
Y_ELECAD	35.00000	0.000000
Y_ELECDLF	220.0000	0.000000
Y_ELECEP	140.0000	0.000000
Y_ELECG	280.0000	0.000000
Y_ELECCOMBUST	0.000000	0.000000
ELECREQ	75835.63	0.000000
ELECIMP	75835.63	0.000000
ELECEXP	0.000000	0.000000
CF_RH	90.00000	0.000000
CF_RS	58.50000	0.000000
CF_BG	10.00000	0.000000
CF_PAW	10.00000	0.000000
CF_EFB	10.80000	0.000000
CF_PKS	12.60000	0.000000
CF_OIL	1.100000	0.000000
CF_CHAR	1260.000	0.000000
CF_SYNGAS	600.0000	0.000000

CF_AFEED	260.0000	0.000000
CF_ETHANOL	3.040000	0.000000
CF_CITRICA	2520.000	0.000000
CF_DLF	720.0000	0.000000
CF_EP	600.0000	0.000000
CF_SYNGASG	400.0000	0.000000
CF_ELECIMP	0.5500000	0.000000
CF_ELECEXP	0.4300000	0.000000
CF_PYF	312.0000	0.000000
CF_PYS	281.0000	0.000000
CF_COMBUSTRS	46.03000	0.000000
CF_COND	60.00000	0.000000
CF_COMBUSTRH	56.54000	0.000000
CF_DACFER	445.0000	0.000000
CF_DALFER	419.0000	0.000000
CF_HWFER	413.6000	0.000000
CF_SEFER	372.0000	0.000000
CF_COMBUSTBG	81.10000	0.000000
CF_FER	320.0000	0.000000
CF_DRYING	60.00000	0.000000
CF_AD	375.0000	0.000000
CF_DLFPRD	99.00000	0.000000
CF_BRIQ	93.60000	0.000000
CF_G	330.0000	0.000000
CF_COMBUSTEFB	24.87000	0.000000
CF_COMBUSTPKS	38.05000	0.000000
C_GP	61526.45	0.000000
X_CO2F	463.0000	0.000000
X_CO2S	404.0000	0.000000
X_COF	0.5800000E-01	0.000000
X_COS	0.5490000E-01	0.000000
X_CH4F	0.3000000E-02	0.000000
X_CH4S	0.3700000E-02	0.000000
X_CO2DACFER	1126.000	0.000000
X_CO2DALFER	1205.000	0.000000
X_CO2HWFER	1154.000	0.000000
X_CO2SEFER	865.6000	0.000000
X_CODACFER	0.3050000	0.000000
X_CODALFER	0.3160000	0.000000
X_COHWFER	0.3240000	0.000000
X_COSEFER	0.2180000	0.000000
X_CH4DACFER	1.124000	0.000000
X_CH4DALFER	1.132000	0.000000
X_CH4HWFER	0.1210000	0.000000
X_CH4SEFER	1.100000	0.000000
X_CO2FER	300.0000	0.000000
X_COFER	0.8100000E-01	0.000000
X_CH4FER	0.3000000E-01	0.000000
X_CO2AD	0.000000	0.000000
X_COAD	0.000000	0.000000
X_CH4AD	0.000000	0.000000
X_N2OAD	0.3000000E-02	0.000000
X_CO2DLF	0.000000	0.000000
X_CO2EP	0.000000	0.000000
X_CO2G	588.6000	0.000000
X_CODLF	0.000000	0.000000
X_COEP	0.000000	0.000000
X_COG	0.8030000E-01	0.000000
X_CH4DLF	0.000000	0.000000
X_CH4EP	0.000000	0.000000
X_CH4G	0.5400000E-02	0.000000

X_CO2COMBUST	0.000000	0.000000
X_COCOMBUST	0.000000	0.000000
X_CH4COMBUST	0.000000	0.000000
FCO2	138327.4	0.000000
FCO	18.92780	0.000000
FCH4	1.686779	0.000000
FN2O	0.000000	0.000000
X_NOXF	0.5530000E-01	0.000000
X_NOXS	0.5490000E-01	0.000000
X_SO2F	0.3000000E-02	0.000000
X_SO2S	0.3700000E-02	0.000000
X_HCF	0.3000000E-02	0.000000
X_HCS	0.3700000E-02	0.000000
X_NOXDACFER	0.3050000	0.000000
X_NOXDALFER	0.3120000	0.000000
X_NOXHWFER	0.3240000	0.000000
X_NOXSEFER	0.2180000	0.000000
X_SO2DACFER	0.7750000	0.000000
X_SO2DALFER	0.6750000	0.000000
X_SO2HWFER	0.5130000	0.000000
X_SO2SEFER	0.7960000	0.000000
X_HCDACFER	0.000000	0.000000
X_HCDALFER	0.000000	0.000000
X_HCHWFER	0.000000	0.000000
X_HCSEFER	0.000000	0.000000
X_NOXFER	0.8000000E-01	0.000000
X_SO2FER	0.1210000	0.000000
X_HCFER	0.000000	0.000000
X_NOXAD	0.000000	0.000000
X_SO2AD	0.1210000	0.000000
X_HCAD	0.4709000	0.000000
X_NOXDLF	0.000000	0.000000
X_NOXEP	0.000000	0.000000
X_NOXG	0.8030000E-01	0.000000
X_SO2DLF	0.000000	0.000000
X_SO2EP	0.000000	0.000000
X_SO2G	0.5400000E-02	0.000000
X_HCDLF	0.000000	0.000000
X_HCEP	0.000000	0.000000
X_HCG	0.5400000E-02	0.000000
X_NOXCOMBUST	0.000000	0.000000
X_SO2COMBUST	0.000000	0.000000
X_HCCOMBUST	25.40600	0.000000
FNOX	18.92631	0.000000
FSO2	1.516477	0.000000
FHC	1.264937	0.000000
X_CODF	60.00000	0.000000
X_CODS	60.00000	0.000000
X_CODDACFER	252.6000	0.000000
X_CODDALFER	255.8000	0.000000
X_CODHWFER	255.3000	0.000000
X_CODSEFER	230.2000	0.000000
X_CODFER	263.0000	0.000000
X_CODAD	-2.522000	0.000000
X_CODDLF	60.00000	0.000000
X_CODEP	0.000000	0.000000
X_CODG	60.00000	0.000000
X_CODCOMBUST	0.2000000E-01	0.000000
FCOD	14157.01	0.000000
Y_WATERPYF	0.2310000E-01	0.000000
Y_WATERPYS	0.2310000E-01	0.000000

Y_WATERDACFER	0.1489000	0.000000
Y_WATERDALFER	0.1510000	0.000000
Y_WATERHWFER	0.1685000	0.000000
Y_WATERSEFER	0.1154000	0.000000
Y_WATERFER	0.2140000E-01	0.000000
Y_WATERAD	0.000000	0.000000
Y_WATERDLF	0.000000	0.000000
Y_WATEREP	0.000000	0.000000
Y_WATERG	0.1380000	0.000000
Y_WATERCOMBUST	0.1800000E-04	0.000000
FWATER	32.35662	0.000000
GWP_CO2	1.000000	0.000000
AP_CO2	0.000000	0.000000
POCP_CO2	0.000000	0.000000
NP_CO2	0.000000	0.000000
ATP_CO2	0.000000	0.000000
TTP_CO2	0.000000	0.000000
ADP_CO2	0.000000	0.000000
HTPE_CO2	0.1000000E-03	0.000000
GWP_CO	0.000000	0.000000
AP_CO	0.000000	0.000000
POCP_CO	0.1470000E-01	0.000000
NP_CO	0.000000	0.000000
ATP_CO	0.000000	0.000000
TTP_CO	0.000000	0.000000
ADP_CO	0.000000	0.000000
HTPE_CO	0.1820000E-01	0.000000
GWP_CH4	23.00000	0.000000
AP_CH4	0.000000	0.000000
POCP_CH4	0.3840000E-02	0.000000
NP_CH4	0.000000	0.000000
ATP_CH4	0.000000	0.000000
TTP_CH4	0.000000	0.000000
ADP_CH4	0.000000	0.000000
HTPE_CH4	0.1500000E-02	0.000000
GWP_NOX	0.000000	0.000000
AP_NOX	1.100000	0.000000
POCP_NOX	1.300000	0.000000
NP_NOX	0.1300000	0.000000
ATP_NOX	0.000000	0.000000
TTP_NOX	0.000000	0.000000
ADP_NOX	0.000000	0.000000
HTPE_NOX	0.000000	0.000000
GWP_N2O	296.0000	0.000000
AP_N2O	0.7000000	0.000000
POCP_N2O	0.3840000E-02	0.000000
NP_N2O	0.000000	0.000000
ATP_N2O	0.000000	0.000000
TTP_N2O	0.000000	0.000000
ADP_N2O	0.000000	0.000000
HTPE_N2O	0.1110000E-01	0.000000
GWP_SO2	0.000000	0.000000
AP_SO2	1.000000	0.000000
POCP_SO2	0.1250000	0.000000
NP_SO2	0.000000	0.000000
ATP_SO2	0.000000	0.000000
TTP_SO2	0.000000	0.000000
ADP_SO2	0.000000	0.000000
HTPE_SO2	0.7690000E-01	0.000000
GWP_HC	0.000000	0.000000
AP_HC	0.1800000E-01	0.000000

POCP_HC	0.4160000	0.000000
NP_HC	0.000000	0.000000
ATP_HC	0.000000	0.000000
TTP_HC	0.000000	0.000000
ADP_HC	0.000000	0.000000
HTPE_HC	0.000000	0.000000
GWP_COD	0.000000	0.000000
AP_COD	0.000000	0.000000
POCP_COD	0.000000	0.000000
NP_COD	0.2200000E-01	0.000000
ATP_COD	0.000000	0.000000
TTP_COD	0.000000	0.000000
ADP_COD	0.000000	0.000000
HTPE_COD	0.000000	0.000000
GWP_COAL	23.02000	0.000000
AP_COAL	0.1770000	0.000000
POCP_COAL	0.000000	0.000000
NP_COAL	0.000000	0.000000
ATP_COAL	0.2081000E-04	0.000000
TTP_COAL	0.6071000E-05	0.000000
ADP_COAL	0.1340000E-01	0.000000
HTPE_COAL	0.000000	0.000000
GWP_OIL	0.000000	0.000000
AP_OIL	0.000000	0.000000
POCP_OIL	0.9230000	0.000000
NP_OIL	0.000000	0.000000
ATP_OIL	0.1639300	0.000000
TTP_OIL	0.2040000E-02	0.000000
ADP_OIL	0.000000	0.000000
HTPE_OIL	0.2000000	0.000000
GWP_CHAR	0.000000	0.000000
AP_CHAR	0.000000	0.000000
POCP_CHAR	0.000000	0.000000
NP_CHAR	0.5037000	0.000000
ATP_CHAR	8.423800	0.000000
TTP_CHAR	0.1687000	0.000000
ADP_CHAR	0.000000	0.000000
HTPE_CHAR	0.000000	0.000000
GWP_SYNGASF	9.156000	0.000000
AP_SYNGASF	0.000000	0.000000
POCP_SYNGASF	0.6360000E-01	0.000000
NP_SYNGASF	0.000000	0.000000
ATP_SYNGASF	0.000000	0.000000
TTP_SYNGASF	0.000000	0.000000
ADP_SYNGASF	0.000000	0.000000
HTPE_SYNGASF	0.4630000E-02	0.000000
GWP_SYNGASS	9.107000	0.000000
AP_SYNGASS	0.000000	0.000000
POCP_SYNGASS	0.3530000E-01	0.000000
NP_SYNGASS	0.000000	0.000000
ATP_SYNGASS	0.000000	0.000000
TTP_SYNGASS	0.000000	0.000000
ADP_SYNGASS	0.000000	0.000000
HTPE_SYNGASS	0.4610000E-02	0.000000
GWP_AFEED	0.000000	0.000000
AP_AFEED	0.000000	0.000000
POCP_AFEED	0.000000	0.000000
NP_AFEED	0.5030000	0.000000
ATP_AFEED	0.000000	0.000000
TTP_AFEED	0.000000	0.000000
ADP_AFEED	0.000000	0.000000

HTPE_AFEED	0.000000	0.000000
GWP_ETHANOL	0.000000	0.000000
AP_ETHANOL	0.000000	0.000000
POCP_ETHANOL	0.4070000	0.000000
NP_ETHANOL	0.000000	0.000000
ATP_ETHANOL	0.7000000E-04	0.000000
TTP_ETHANOL	0.1100000E-03	0.000000
ADP_ETHANOL	0.000000	0.000000
HTPE_ETHANOL	0.1000000E-03	0.000000
GWP_CITRICA	0.000000	0.000000
AP_CITRICA	0.000000	0.000000
POCP_CITRICA	0.4070000	0.000000
NP_CITRICA	0.000000	0.000000
ATP_CITRICA	0.3610000E-02	0.000000
TTP_CITRICA	0.1500000E-03	0.000000
ADP_CITRICA	0.000000	0.000000
HTPE_CITRICA	0.000000	0.000000
GWP_DLF	0.000000	0.000000
AP_DLF	0.000000	0.000000
POCP_DLF	0.000000	0.000000
NP_DLF	0.000000	0.000000
ATP_DLF	0.000000	0.000000
TTP_DLF	0.000000	0.000000
ADP_DLF	0.000000	0.000000
HTPE_DLF	0.000000	0.000000
GWP_EP	0.000000	0.000000
AP_EP	0.000000	0.000000
POCP_EP	0.9230000	0.000000
NP_EP	0.000000	0.000000
ATP_EP	0.1639300	0.000000
TTP_EP	0.2040000E-02	0.000000
ADP_EP	0.000000	0.000000
HTPE_EP	0.2000000	0.000000
GWP_SYNGASG	0.6248000	0.000000
AP_SYNGASG	0.000000	0.000000
POCP_SYNGASG	0.3800000E-02	0.000000
NP_SYNGASG	0.000000	0.000000
ATP_SYNGASG	0.000000	0.000000
TTP_SYNGASG	0.000000	0.000000
ADP_SYNGASG	0.000000	0.000000
HTPE_SYNGASG	0.4810000E-02	0.000000
FCOAL	9315.272	0.000000
FCOAL_SUB	69011.40	0.000000
FCOAL_SUB_ELEC	0.000000	0.000000
GWP	-1235778.	0.000000
AP	-10543.86	0.000000
POCP	97965.32	0.000000
NP	24156.48	0.000000
ATP	412687.2	0.000000
TTP	8132.539	0.000000
ADP	-799.9282	0.000000
ISI_DLF	12.00000	0.000000
ISI_EP	13.00000	0.000000
ISI_G	34.00000	0.000000
ISI_PYF	31.00000	0.000000
ISI_PYS	30.00000	0.000000
ISI_DACFER	22.00000	0.000000
ISI_DALFER	22.00000	0.000000
ISI_HWFER	24.00000	0.000000
ISI_SEFER	26.00000	0.000000
ISI_CITRIC	25.00000	0.000000

ISI_AD	30.00000	0.000000
ISI_AFEED	9.000000	0.000000
ISI_FERTILISER	15.00000	0.000000
ISI_COMBUST	35.00000	0.000000
ISI	123.0000	0.000000
HTPE	21230.09	0.000000
HTPI	8132.539	0.000000
JC_DLF	0.2000000E-02	0.000000
JC_EP	0.2150000E-01	0.000000
JC_GASPY	0.4000000E-02	0.000000
JC_ETHANOL	0.1000000E-01	0.000000
JC_CITRIC	0.5000000E-02	0.000000
JC_AD	2.210000	0.000000
JC_AFEED	0.4000000E-03	0.000000
JC_COMBUST	0.5760000	0.000000
JC	281.7675	0.000000
W_EC	0.5000000	0.000000
LAMDA_EC	0.9998545	0.000000
W_EN	0.2500000	0.000000
LAMDA_EN	0.3747795	0.000000
W_SC	0.2500000	0.000000
LAMDA_SC	0.4469642	0.000000
W_GWP	0.1250000	0.000000
LAMDA_GWP	0.9988961	0.000000
W_AP	0.1250000	0.000000
LAMDA_AP	0.9990170	0.000000
W_POCP	0.1250000	0.000000
LAMDA_POCP	0.9665741E-03	0.000000
W_NP	0.1250000	0.000000
LAMDA_NP	0.1728028E-05	0.000000
W_ATP	0.1250000	0.000000
LAMDA_ATP	0.5081569E-06	0.000000
W_TTP	0.1250000	0.000000
LAMDA_TTP	0.1302074E-05	0.000000
W_ADP	0.1250000	0.000000
LAMDA_ADP	0.9990013	0.000000
W_WATER	0.1250000	0.000000
LAMDA_WATER	0.3516391E-03	0.000000
W_HTPI	0.2500000	0.000000
LAMDA_HTPI	0.1302074E-05	0.000000
W_HTPE	0.2500000	0.000000
LAMDA_HTPE	0.8006398E-03	0.000000
W_JOB	0.2500000	0.000000
LAMDA_JOB	0.9985932	0.000000
W_ISI	0.2500000	0.000000
LAMDA_ISI	0.7884615	0.000000
LAMDA	0.000000	0.000000