Research Proposal for PhD Programme

SYHTHESISE A SUSTAINABLE SAGO INDUSTRY

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ABSTRACT

Various sago biomass (i.e., sago barks, fibres and wastewater) that potentially converted into value-added products are generated during sago starch extraction process (SSEP). In current industrial practices, such biomass are disposed to the environment and caused severe environmental issues. Therefore, in order to minimise the environmental impacts and to improve economic performance of sago industry, sago biomass is vital to be recovered. On the other hand, a sustainable sago value chain, which involved activities plantation, harvesting, sago starch extraction process (SSEP), and transportations, is synthesised in this thesis via Fuzzy Multi-Footprint Optimisation (FMFO) approach. This proposed approach considered carbon, water, and workplace footprints as well as economic performance of sago value chain. In order to trade-off the conflicts among the optimisation objectives, the concept of fuzzy optimisation is adopted in this approach. Then, recovery of sago biomass in SSEP is focused. In order to prioritise sago biomass for recovery in sago industry, Material Flow Cost Accounting (MFCA)-based prioritisation approach is developed in this thesis. This MFCA-based approach introduced hidden cost (HC) and carry-forward cost (CFC) to determine cost associated with waste streams. Based on the associated cost, waste streams can be prioritised for recovery. Then, this MFCA-based prioritisation approach is further extended as extended MFCA (eMFCA)-based approach to simultaneous synthesise total resource conservation network (RCN) with industrial processes. In this thesis, total water network and SSEP is synthesised simultaneously via eMFCA-based approach. Furthermore, techno-economic and environmental performance of conversion of sago barks and fibres into combined heat and power (CHP) and bioethanol is evaluated. In addition, sensitivity analysis on payback period is conducted in different scenarios due to variation of feedstock cost, enzyme cost, and labour cost. In order to further improve sustainability of sago industry, a conceptual integrated sago-based biorefinery (SBB) is envisaged. Maali's method is adopted in this thesis to allocate the benefits of each party participating in integrated SBB. Lastly, conclusions and future works are included in the end of this thesis.

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NOMENCLATURE

Abbreviation

ACA	Alternate Cost Avoided
BK	bark
BFW	boiler feed water
BIO	biological
BOD	biochemical oxygen demand
BTG	Betong
BTL	Bintulu
CFC	carry-forward cost
CFP	carbon footprint
CHARMEN	combined heat and reactive mass exchange network
CHEM	chemical
CHP	combined heat and power
CO_2	carbon dioxide
COD	chemical oxygen demand
CPU	central processing unit
CWR	crop water requirement
D	death
DAP	diammonium phosphate
DBK	debarking
DCF	discounted cash flow
DLT	Dalat

DOSH	Department of Occupational Safety and Health
DP	drying and packing
EF	emission factor
EIA	Energy Information Administration
EIPs	eco-industrial parks
EQ	equalisation
FBR	fibre
FILT	filtration
FMFO	Fuzzy Multi-Footprint Optimisation
FSEP	fibre separation
GCA	gas cascade analysis
GHG	greenhouse gases
HC	hidden cost
HL	hire new labour
HMF	hydroxymethyl furfural
HP	high pressure
HPS	high pressure steam
HRSG	heat recovery steam generator
HUC	hidden unit cost
IE	industrial ecology
IS	industrial symbiosis
KCH	Kuching
LCA	life cycle assessment
LCO	life cycle optimisation
LHV	lower heating value

LP	linear programming
LPS	low pressure steam
MBR	membrane bioreactor
MEN	mass-exchange network
MFCA	Material Flow Cost Accounting
MILP	mixed integer linear program
MINLP	mixed integer non linear programming
MR	Miri
MRD	Meradong
MRPD	Material Recovery Pinch Diagram
MRR	Maximum Resource Recovery
MRY	Malaysia Ringgit
MSCC	Material Surplus Composite Curve
MUK	Mukah
MWR	maximum water recovery
N/A	not applicable
NH_3-N	ammoniacal nitrogen
NLP	non-linear programming
NO_x	generic term for mono-nitrogen oxides NO (nitric oxide) and NO_2 (nitrogen dioxide)
NPD	non-permanent disability
NREL	National Renewable Energy Laboratory
odt	oven dry tonne
PC	processing cost
PCBs	printed circuit boards

PD	permanent disability
PFD	process flow diagram
PI	process integration
PP	power plants
PSO	Particle Swarm Optimisation
PWR	product water requirement
RAIN	requires minimum rainfall
RCNs	Resource Conservation Networks
REAMEN	Reactive Mass-Exchange Network
RO	reverse osmosis
RPG	rasping
RP	recycle percentage
RW	river water
SA	Sri Aman
SB	Sibu
SBB	sago-based biorefinery
SBP	sago-based bioethanol plant
SIEV	sieving
SMH	Samarahan
SLUD	sludge
SMJ	Simunjan
SNG	synthetic natural gas
SRK	Sarikei
SRN	Serian
SRT	Saratok

SSEP	sago starch extraction process
Std. A	Standard A
SWSEP	starch water separation
TAWF	total average water footprint
TCI	total capital investment
TDS	total dissolved solid
TERT	tertiary
THC	total hidden cost
TS	total sites
TSS	total suspended solid
TKN	total kjeldahl nitrogen
TT	Tatau
UCL	use current available labour
VCA	value chain analysis
VHP	very high pressure
WCA	water cascade analysis
WFA	water footprint analysis
WFP	water footprint
WPFP	workplace footprint
WTP	water treatment plant
WW	wastewater
WWTP	wastewater treatment plant

Indices

b	index for contaminant
b'	index for biomass boiler
d	index for company or plant
e	index for energy
f	index for sago processing system
g	index for sago plantation
h	index for process source
i	index for process
i'	index for upstream and downstream process of process *i*
j	index for port
j'	index for process sink
k	index for intermediate material
l	index for categories of manpower
m	index for bioresources
m'	index for raw material
p	index for product
pp	index for power plant
q	index for recycled waste
S	index of coalition
t	index for treatment unit
u	index for customer
w	index for waste
y	index for district

y'	index for waste to be disposed to the environment
ℵ	index of set of all companies/plants from coalition *S*

Parameters

C_p	heat capacity of water, kJ/kg.K
$CARBON_{TERT}$	total required amount of carbon, kg
$CARBON^{REQ}_{COD}$	total carbon required per kg of COD removed, kg
$CC^{IN}_{TERT,COD}$	inlet concentration of COD to tertiary process, ppm
CC^{DIS}_{b}	discharged concentration limit of pollutants *b*, g/m^3
CC^{LIMIT}_{b}	discharge limit of contaminant *b*, ppm
$CC^{MAX}_{j',b}$	maximum inlet concentration of contaminant *b* of process sink *j'*, ppm
$CC^{OUT}_{h,b}$	fixed concentration of contaminant *b* of process source, *h*, ppm
$CC^{OUT}_{f,p,b}$	concentration of pollutant *b* of discharged water from sago processing system *f* during product *p* production, g/m^3
CC^{SLUD}_{t}	concentration of sludge generated in treatment unit *t*, ppm
CF^{L_TON}	conversion factor of volume from litre to tonne
$Cost^{ENGY}_{i}$	energy costs of process *i*, USD
$Cost^{MAT}_{i}$	material costs of process *i*, USD
$Cost^{PC}_{i}$	processing cost of process *i*, USD

$\text{Cost}_i^{\text{SYM}}$	system costs of process *i*, USD
$\text{Cost}_{i,y',b}$	waste discharge unit cost of discharged waste *y'* with parameter *b* of waste quality for process *i*, USD/kg
CWR	crop water requirement, m^3/t
$d_{f,j}$	actual travel distances between sago processing system *f* and ports *j*, km
$d_{g,f}$	actual travel distances between plantation *g* and sago processing system *f* , km
$d_{j,u}$	actual travel distances between ports *j* and customer *u*, km
$D_{p,u}^{\text{LL}}$	lower limits of the product *p* demand of customer *u*, t/y
$D_{\text{starch},u}^{\text{LL}}$	lower limits of the starch demand of customer *u*, t/y
$D_{p,u}^{\text{UL}}$	upper limits of the product *p* demand of customer *u*, t/y
$D_{\text{starch},u}^{\text{UL}}$	upper limits of the starch demand of customer *u*, t/y
$D_{u,p}$	product *p* demand of customer *u*, t/y
$\text{DOSE}_{t,c}$	dosage of chemical *c* required in treatment unit *t*, ppm
$\text{DRY}_{\text{DIS}}^{\text{SLUD}}$	dryness of sludge after the sludge treatment process, kg/m^3
$E_{f,p}$	power consumption of sago processing system *f* for production of product *p*, kWh/kg
$E_{i,e}$	amount of energy types *e* in process *i*, kWh
E_k^{In}	calorific value of biomass *k* fed into the boiler, kJ/g

E^{Out}	total extractable energy from biomass boiler, kW
$E^{Out}_{k,b'}$	total extractable energy from biomass *k* via boiler *b'*, kW
EF_{pp}	emission factor of power plants, kg CO_2/kWh
EF^{ELEC_FS}	carbon emission factor of electricity generation from fossil fuel, kgCO_2/kWh
EF^{Fuel_Power}	carbon emission factor of electricity generation from fossil fuel, kgCO_2/kWh
EF^{Fuel_Road}	emission factor of road transportation, kgCO_2/km-t
EF^{Fuel_Sea}	emission factor of sea transportation, kgCO_2/km-t
EF^{GF}	emission factor of gasoline as transportation fuel, kgCO_2 equivalent/MJ
EF^{Grid}	emission factor of grid power, kg CO_2/kWh
EF^{Power}	emission factor of power generation, kgCO_2/kWh
ER^{Road}	energy requirement for road transportation, MJ/km-t
ER^{Sea}	energy requirement for sea transportation, MJ/km-t
$F^{In}_{f,p}$	total volume of inlet water of sago processing system *f* to produce one ton of product *p*, m^3/t
$F^{Out}_{f,p}$	total volume of outlet water of sago processing system *f* to produce one ton of product *p*, m^3/t
F_h	waste flowrate of process source, *h*, t/d
FWR	required freshwater, m^3/t
Δh_{vap}	enthalpies of vaporisation of water, kJ/kg
h_v	specific enthalpy of saturated steam, kJ/kg

h_{sup}	specific enthalpy superheated steam, kJ/kg
K_g^{Plant}	total palms in one hectare of plantation *g* annually, palm/ha.y
$K_{i',h,k}$	intermediate material *k* sent from process *i'* to process source *h*, t/d
$K_{i,i',k}$	intermediate material *k* that sent from process *i* to process *i'*, t/d
$K_{i',i,k}$	amount of intermediate material *k* from process *i'* to process *i*, t/d
$K_{i',j',k}$	flowrate of intermediate material *k* that sent from process *i'* to process sink *j'*, t/d
KA	cost charged by Kualiti Alam, USD/t
$L_{g,p}$	extractable product *p* from sago log that comes from plantation *g*, t/log
$L_{g,\mathrm{starch}}$	extractable starch from sago log that comes from plantation *g*, t/log
$L_{i,l}$	manpower *l* involved in process *i*, person/d
LAND	cost charged by Landfill, USD/t
$LHV^{ETHANOL}$	lower heating value of ethanol, MJ/l
$M_{f,p,b}^{Out}$	load of pollutant *b* of discharged water from sago processing system *f* during product *p* production, g/t
$M_{i,m'}$	amount of raw material *m'* in process *i*, t
M_k^{In}	intake of biomass *k* fed into the boiler, g/s

M_{SC}^{SAL}	amount of recycled aluminium needed from external facilities to SC process, t
n^{CPT}	number of containers in a single trip, container/trip
OPH_c	operating hours of configuration *c*, h
$OPHR_{m'}^{SBB}$	operation hour of integrated SBB using raw material *m'*, h/d
$P_{i,p}$	amount of desired products *p* in process *i*, t
PWR	product water requirement, m^3/t
PW_{pp}	power generated by individual power plant, kWh
$QLT_{i,y',b}$	effluent waste quality in parameter *b* of discharged waste *y'* of process *i*, ppm
$q_{g,Log}$	average weight of sago log, t/log
RAIN	requires minimum rainfall, mm/y
r^{Sea_D}	death risk of sea transportation, deaths/km
$r_f^{Process\_D}$	death risk of processing in sago processing system *f*, deaths/t
$r_g^{Harv\_D}$	death risk of harvesting in plantation *g*, deaths/palm
$r_j^{Port\_D}$	death risk of port handling in port *j*, deaths/t
$r_y^{Road\_D}$	death risk of road transportation in district *y*, deaths/km
$S_{g,p}$	annual yield of product *p* of plantation *g*, t/ha-y
S_c^{SLUD}	sludge generation yield due to the usage of chemical *c*

$S_{t,b}^{SLUD}$	sludge generation yield in treatment unit *t* caused by removal of contaminant *b*
$SP_{starch,j,u}$	selling price of starch from port *j* to customer *u*, MYR/kg
$SP_{g,f}^{Log}$	selling price of sago logs from plantation *g* to sago processing system *f*, MYR/log
$SP_{f,p,j}^{ProSys\_Por\ t}$	selling price of product *p* from sago processing system *f* to port *j*, MYR/kg
$SP_{f,starch,j}^{ProSys\_Por\ t}$	selling price of starch from sago processing system *f* to port *j*, MYR/kg
$SP_{p,j,u}^{Port\_Cust}$	selling price of product p from port *j* to customer *u*, MYR/kg
$STD_{i,b}$	standard discharge limit of waste in parameter *b*, ppm
T_{BFW}	temperature of BFW, ^{o}C
T_{sat}	saturation temperature of steam, ^{o}C
T_{h}^{OUT}	total outlet of process source *h*, t/d
T_{i}^{OUT}	total output of process *i*, t/d
$T_{i'}^{OUT}$	total output of process *i'*, t/d
T_{sc}^{OUT}	total output of SC process, t/d
$UCost_{f,starch,j}$	unit cost of starch from sago processing system *f* to port *j*, MYR/kg
$UCost^{Road}$	unit cost of road transportation, MYR/km

$\text{UCost}_{f,p}^{\text{Process}}$	unit cost of processing in sago processing system *f* into product *p*, MYR/t
$\text{UCost}_{g}^{\text{Harv}}$	unit cost of harvesting, MYR/palm
$\text{UCost}_{g,f}^{\text{Log}}$	unit cost of sago log that sell from plantation *g* to sago processing system *f*, MYR/log
$\text{UCost}_{i,e}$	unit cost of energy *e* for process *i*, USD/kWh
$\text{UCost}_{i,l}$	unit cost of manpower *l* for process *i*, USD/d
$\text{UCost}_{i,m'}$	unit cost of raw materials *m'* for process *i*, USD/m^3 or USD/log or USD/t
$\text{UCost}_{j}^{\text{Handling}}$	handling unit cost in port *j* (MYR/container)
$\text{UCost}_{j,u}^{\text{Port\_Cust}}$	sea freight cost from port *j* to customer *u* (MYR/trip),
$\text{UCost}_{p,j}^{Port}$	purchasing unit cost of product *p* in port *j* (MYR/kg),
$V_{f,p}$	conversion rate to product *p* in sago processing system *f*, unitless
$V_{g,\text{Log}}$	conversion rate of palm to log from plantation *g*, log/palm
$V_{g,m}$	conversion rate of palm to bioresource *m* in plantation *g,* log/palm or t/palm
$V_{f,\text{starch}}$	conversion rate of log to starch
$W_{i,w}$	amount of generated waste of process *i*, t/d
WR_{pp}	volume of water demand for individual power plant, m^3/kWh

WR^{Power}	water required for power generation, m^3/kWh
WR^{Road}	water required for road transportation, m^3/kg.km
WR^{Sea}	volume of water to deliver products to customers via sea transportation, m^3/km-t
Z^{Lorry}	lorry capacity, t/trip
Z^{TEU}	capacity of a standard shipping container, t/container
$Z_{f,p}^{ProSys}$	annual production capacity of sago processing system f for product *p*, t/y
Z_{g}^{Palm}	annual available sago palms in plantation *g*, palm/y
Z_{j}^{Port}	port *j* capacity, t/y
$\eta_{t,b}$	removal efficiency of contaminant *b* in treatment unit *t*, %
$\eta_{TERT, COD}$	removal efficiency of COD in tertiary process, %
$\eta_{b'}^{Boiler}$	efficiency of boiler *b'*, %
η^{Boiler}	efficiency of boiler, %

Variables

$BETH_{m'}^{SBB\_Generated}$	bioethanol produced in integrated SBB using raw material *m'*, t/d
C_d	Marginal contributions for each company/plant *d*
$CC_{j',b}^{IN}$	total inlet concentration of contaminant *b* of process sink *j'*, ppm
$CC_{t,b}^{IN}$	total inlet concentration of contaminant *b* of treatment unit *t*, ppm

$CC_{t',b}^{\mathrm{OUT}}$	concentration of contaminant *b* of treatment unit *t'*, ppm
CFP^{LL}	lower fuzzy limit of CFP, $kgCO_2$/y
CFP^{UL}	upper fuzzy limit of CFP, $kgCO_2$/y
$CFP_{m'}^{SBB\_Reduced}$	reduced carbon footprint of the integrated SBB, $kgCO_2$/d
$Cost_{h,j'}$	cost carried from process source *h* to process sink *j'*, USD/d
$Cost_{h,t}$	cost carried from process source *h* to treatment unit *t*, USD/d
$Cost_{i',h,k}$	cost carried by the intermediate material *k* that sent from process *i'* to process source *h*, USD/d
$Cost_{i',i,k}$	cost carried by intermediate material *k* from process *i'* to process *i* , USD/d
$Cost_{i',i,q}$	cost carried by the direct reused/recycled waste *q* from process *i'* to process *i*, USD/d
$Cost_{i',j',k}$	cost carried by intermediate *k* that sent from process *i'* to process sink *j'*, USD/d
$Cost_{t,j'}$	cost carried from treatment unit *t* to process sink *j'*, USD/d
$Cost_{t',t}$	cost carried from treatment unit *t'* to treatment unit *t*, USD/d
$Cost_{h}^{\mathrm{CFC}}$	carry-forward cost of process source *h*, USD/d
$Cost_{i}^{\mathrm{CFC}}$	carry-forward cost to process *i*, USD
$Cost_{j'}^{\mathrm{CFC}}$	carry-forward cost of process sink *j'*, USD/d

$Cost_t^{\mathrm{CFC}}$	carry-forward cost of treatment unit *t*, USD/d
$Cost_h^{\mathrm{HC}}$	hidden cost of process source *h*, USD/d
$Cost_i^{\mathrm{HC}}$	hidden cost of process *i*, USD/d
$Cost_{i'}^{\mathrm{HC}}$	hidden cost of process *i'*, USD/d
$Cost_{i,p}^{\mathrm{HC}}$	hidden cost of product of process *i*, USD
$Cost_{i,w}^{\mathrm{HC}}$	hidden cost of waste of process *i*, USD
$Cost_{j'}^{\mathrm{HC}}$	hidden cost of process sink *j'*, USD/d
$Cost_t^{\mathrm{HC}}$	hidden cost of treatment unit *t*, USD/d
$Cost_{\mathrm{SLUD}}^{\mathrm{HC}}$	hidden cost of sludge unit, USD/d
$Cost_{\mathrm{TERT}}^{\mathrm{HC}}$	hidden cost of tertiary treatment unit, USD/d
$Cost_i^{\mathrm{HC,\ Y'}}$	hidden cost of disposal waste *y'* of process *i*, USD/d
$Cost_t^{\mathrm{HC,\ Y'}}$	hidden cost of disposal waste *y'* of treatment unit *t*, USD/d
$Cost_{\mathrm{SLUD}}^{\mathrm{HC,Y'}}$	hidden cost of disposal sludge, USD/d
$Cost_{\mathrm{TERT}}^{\mathrm{HC,\ Y'}}$	hidden cost of discharged water, USD/d
$Cost_h^{\mathrm{HUC}}$	hidden unit cost of process source *h*, USD/d
$Cost_i^{\mathrm{HUC}}$	hidden unit cost of process *i*, USD
$Cost_{i'}^{\mathrm{HUC}}$	hidden unit cost of process *i'*, USD/d
$Cost_t^{\mathrm{HUC}}$	hidden unit cost of treatment unit *t*, USD/d
$Cost_{t'}^{\mathrm{HUC}}$	hidden unit cost of treatment unit *t'*, USD/d

$Cost_{i',i,k}$	intermediate materials costs from process *i'* to process *i*, USD
$Cost^{MGT}$	waste management cost, USD/d
$Cost_i^{\mathrm{MGT}}$	management cost of process *i*, USD
$Cost_h^{\mathrm{PC}}$	processing cost of process source, *h*, USD/d
$Cost_i^{\mathrm{PC}}$	processing cost of process *i*, USD/d
$Cost_{j'}^{\mathrm{PC}}$	processing cost of process sink *j'*, USD/d
$Cost_t^{\mathrm{PC}}$	processing cost of treatment unit *t*, USD/d
$Cost^{THC,Y'}$	total hidden cost of disposal waste, USD/d
$ELEC_{m'}^{SBB\_Generated}$	electricity generated in integrated SBB using raw material *m'*, kW
EP^{LL}	lower fuzzy limit of economic potential, MYR/y
EP^{UL}	upper fuzzy limit of economic potential, MYR/y
$F_{h,j'}$	waste flowrate sent from process source *h* to process sink *j'*, t/d
$F_{h,t}$	waste flowrate sent from process source *h* to treatment unit *t*, t/d
$F_{t,j'}$	waste flowrate sent from treatment unit *t* to process sink *j'*, t/d
$F_{t,t'}$	waste flowrate sent from treatment unit *t* to treatment unit *t*', t/d
$F_{t',t}$	waste flowrate sent from treatment unit *t*' to treatment unit *t*, t/d
F_t^{DIS}	total flowrate discharged to environment, t/d

$F_{j'}^{\mathrm{IN}}$	inlet flowrate of process sink *j'*, t/d
F_{t}^{IN}	inlet flowrate of treatment unit *t*, t/d
$F_{\mathrm{TERT}}^{\mathrm{IN}}$	inlet flowrate of tertiary process, t/d
F_{t}^{OUT}	outlet flowrate of treatment unit *t*, t/d
F^{SLUD}	total sludge flowrate, t/d
F_{t}^{SLUD}	flowrate of sludge generated in treatment unit *t*, t/d
$F_{\mathrm{DIS}}^{\mathrm{SLUD}}$	disposal sludge amount, t/d
H_g	total palms that harvested annually from plantation *g*, palm/y
$m_{\mathrm{k,b'}}^{\mathrm{Steam}}$	mass flow rate of steam generated from biomass *k* and boiler *b'*, kg/s
n	total number of companies or plants
$n_{f,p,j}^{\mathrm{Trip}}$	number of trips for product *p* delivery from sago processing system *f* to port *j*, trip/y
$n_{g,f}^{\mathrm{Trip}}$	required number of trips from plantation *g* to sago processing system *f*, trip/y
$n_{p,j,u}^{\mathrm{Ctn}}$	number of containers required to be shipped from ports *j* to customers *u* for product *p* delivery, container/y
$Q_{i',\mathrm{SC}}$	amount of recycled waste from process *i'* to secondary casting process, t
$Q_{i,i',q}$	flowrate of direct reused/recycled waste *q* that reused/recycled from process *i* to process *i'*, t/d

$Q_{i',\text{sc}}^{\text{SAL}}$	amount of recycled waste of process *i'* to SC process, t
$R^{\text{D\_LL}}$	lower fuzzy limit of death risk, death/y
$R^{\text{D\_UL}}$	upper fuzzy limit of death risk, death/y
$R^{\text{NPD\_LL}}$	lower fuzzy limit of NPD risk, NPD/y
$R^{\text{NPD\_UL}}$	upper fuzzy limit of NPD risk, NPD/y
$R^{\text{PD\_LL}}$	lower fuzzy limit of PD risk, PD/y
$R^{\text{PD\_UL}}$	upper fuzzy limit of PD risk, PD/y
$RP_{\text{SC}}^{\text{SAL}}$	recycle percentage of SAL in SC process
$SALC$	recycled aluminium cost, USD
$T_{\text{SLUD}}^{\text{OUT}}$	total output of sludge unit, t/d
T_t^{OUT}	total output of treatment unit *t*, t/d
$T_{\text{TERT}}^{\text{OUT}}$	total output of tertiary treatment unit , t/d
$TotCFP$	total CFP of sago value chain, $kgCO_2$/y
$TotCFP^{\text{Fuel\_ProSys\_Port}}$	total fuel-based CFP from sago processing system to ports, $kgCO_2$/y
$TotCFP^{\text{Fuel\_Plant\_ProSys}}$	total fuel-based CFP from plantations to sago processing system, $kgCO_2$/y
$TotCFP^{\text{Fuel\_Port\_Cust}}$	total fuel-based CFP from ports to customers, $kgCO_2$/y
$TotCFP^{\text{Power}}$	total power-based CFP, $kgCO_2$/y
$TotCost^{\text{Handling}}$	total handling cost, MYR/y
$TotCost^{\text{Harv}}$	total harvesting cost, MYR/y
$TotCost^{\text{ProSys}}$	total cost of sago processing system, MYR/y
$TotCost^{\text{ProSys\_Port}}$	total transportation cost from sago processing system to ports, MYR/y

$TotCost^{\text{Plant}}$	total costs of plantations, MYR/y
$TotCost^{\text{Plant\_ProSys}}$	total transportation cost from plantations to sago processing system, MYR/y
$TotCost^{\text{Port}}$	total cost of ports, MYR/y
$TotCost^{\text{Port\_Cust}}$	sea freight cost from port to customer, MYR/y
$TotCost^{\text{Process}}$	total processing cost, MYR/y
$TotCost^{\text{Prod}}$	total purchasing cost of products p in sago processing system, MYR/y
$TotCost^{\text{RawMat}}$	total raw material cost, MYR/y
$TotEP$	economic potential of sago value chain, MYR/y
$TotEP^{\text{ProSys}}$	economic potential of sago processing system, MYR/y
$TotEP^{\text{Plant}}$	economic potential of plantations, MYR/y
$TotEP^{\text{Port}}$	economic potential of ports, MYR/y
$TotR^{\text{D}}$	total death risk of sago value chain, death/y
$TotR^{\text{Harv\_D}}$	total harvesting death risk, death/y
$\text{TotR}^{\text{ProSys\_Port\_D}}$	total road transportation death risks (from sago processing system to port), death/y
$\text{TotR}^{\text{Plant\_ProSys\_D}}$	total road transportation death risks (from plantation to sago processing system), death/y
$TotR^{\text{Port\_D}}$	total handling death risk, death/y
$TotR^{\text{Process\_D}}$	total processing death risk, death/y
$TotRV^{\text{ProSys}}$	total revenue of sago processing system, MYR/y
$TotRV^{\text{Plant}}$	total revenue of plantations, MYR/y
$TotRV^{\text{Port}}$	total revenue of ports, MYR/y
$TotR^{\text{Sea\_D}}$	total sea transportation death risk, death/y

$TotWFP$	total WFP of sago value chain, m^3/y
$TotWFP^{\text{Blue}}$	total blue WFP, m^3/y
$TotWFP^{\text{Green}}$	total green WFP, m^3/y
$TotWFP^{\text{Grey}}$	total grey WFP, m^3/y
$TotWFP^{\text{Power}}$	total power-based WFP, m^3/y
$TotWFP^{\text{Road\_ProSys\_Port}}$	total WFP of road transportation from sago processing system to ports, m^3/y
$TotWFP^{\text{Road\_Plant\_ProSys}}$	total WFP of road transportation from plantations to sago processing system, m^3/y
$TotWFP^{\text{Sea\_Port\_Cust}}$	total WFP of sea transportation from ports to customers, m^3/y
x_d	payoffs of companies/plants *d*
$X_{f,p}^{\text{ProSys}}$	amount production of product *p* in sago processing system *f*, t/y
$X_{f,\text{starch}}^{\text{ProSys}}$	amount production of starch in sago processing system *f*, t/y
$X_{f,p,j}^{\text{ProSys\_Port}}$	total amount of product *p* that sent from sago processing system *f* to port *j*, t/y
$X_{g,m}^{\text{Plant}}$	total amount of bioresource *m* produced in plantation *g*, log/y or t/y
$X_{g,\text{Log}}^{\text{Plant}}$	total amount of sago log produced in plantation *g*, log/y
$X_{g,f}^{\text{Plant\_ProSys}}$	total amount of sago log from plantation *g* to sago processing system *f*, log/y

X_{j}^{Port}	total product *p* sent to port *j*, t/y
$X_{p,j}^{\text{Port}}$	amount product *p* to port *j*, t/y
$X_{p,j,u}^{\text{Port\_Cust}}$	amount of product *p* that is shipped from port *j* to customer *u*, t/y
$X_{\text{starch},j,u}^{\text{Port\_Cust}}$	amount of starch that is shipped from port *j* to customer *u*, t/y
$v(S)$	characteristics function value
WFP^{LL}	lower fuzzy limit of WFP
WFP^{UL}	upper fuzzy limit of WFP
$Y_{i,y'}$	amount of disposal waste *y'* of process *i*, t/d
β	independent continuous variable
λ	fuzzy degree of satisfaction

CHAPTER 1

INTRODUCTION

1.1 Background

Sago palm is a species of genus *Metroxylon*, given a scientific name as *Metroxylon sagu* (Flach, 1997). It is an underutilised crop which thrives in swampy area and acidic peat soil. In general, sago palm grows in wild and can be found in tropical lowland forest in South East Asia countries and Papua New Guinea (Flach, 1997).

Sago palm is considered as "starch crop of the 21st century" as it has strong ability to sustain and thrive in most soil conditions (Jong, 1995). The main product of sago palm is known as sago starch. Such starch is accumulated in sago trunk during the growth cycle of sago palm and can be extracted from the trunk via sago starch extraction process (SSEP) in sago mills. Sago starch is one of the important foods for human as it has high content of carbohydrate. In addition, it can be converted into food products (e.g., noodles, cakes, biscuits, etc.) and non-food products (e.g., ethanol, sugar, kojic acid, etc) via different technologies (Singhal et al., 2008). Besides, sago starch can also be used as meal replacement for rice (Tribunnews.com, 2014).

The top three producers of sago starch in the world include Papua New Guinea, Indonesia and Malaysia (Singhal et al., 2008). Indonesia is the world's largest producer of sago starch (Agriculture Research and Development Body, 2014). There are 5.2 million hectares of sago plantation areas in Indonesia (Tribunnews.com, 2014). The spread of sago plantation does not only occur in Eastern Indonesia but also in Papua, Maluku, North Sulawesi, Central Sulawesi, South Sulawesi, South Kalimantan, West Kalimantan, Jamb, West Sumatra, and Riau (Tribunnews.com, 2014). Since sago starch has the average production rate of 20 – 40 tonnes per hectare (Tribunnews.com, 2014), about 100 – 200 million tonnes of starch are produced from the 5 million hectares of sago land area.

On the other hand, sago palm in Malaysia is mostly grown in Sarawak. Sarawak possessed about 55 thousand hectares of sago plantation area in year 2013 (Department of Agriculture Sarawak, 2016). These plantations are mostly located in districts Dalat, Mukah, Betong, and Saratok of Sarawak (Department of Agriculture Sarawak, 2016). Besides, there are about nine sago mills in Sarawak which produce sago starch. These sago mills are mainly located in Mukah and Dalat. The produced starch is then supplied to local customers or exported to different foreign customers such as Japan, Singapore, Taiwan, Thailand, United stated, Vietnam, etc. (Department of Agriculture Sarawak, 2016). Note that sago starch is one of the important export goods in Malaysia (Department of Agriculture Sarawak, 2016). In order to produce sago starch, sago palms are cultivated and planted for 9 to 12 years. Once the sago palms are mature, the mature sago palms are harvested and cut into logs at the plantation area. The sago logs are then transported to sago mills via road and river transportation for sago starch extraction. The starch is then either supplied to local customers via road transportation or exported to foreign customers via sea transportation using different ports. All these activities (plantation, harvesting, starch extraction, and transportations) formed a sago value chain as shown in Figure 1.1.

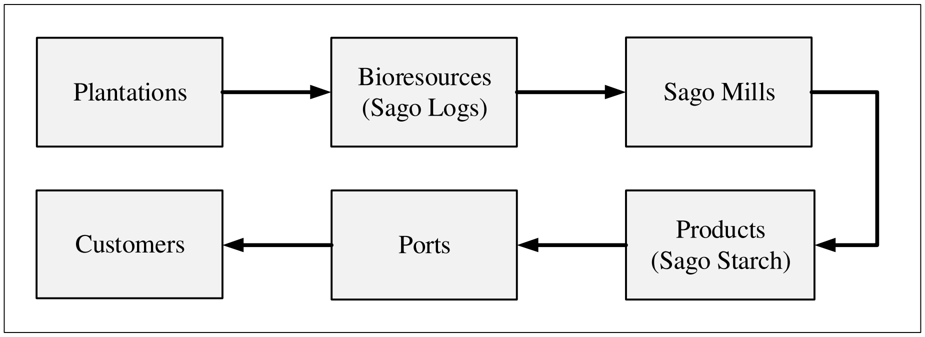

Figure 1.1: Sago value chain

The detailed process of plantation, harvesting, and sago starch extraction process (SSEP) in sago mills are described in following sections.

1.2 Plantation

Sago palms are first cultivated via nursery process using baby shoots. Baby shoots are cultivated and turned into young sago shoots before they are transferred to new sago plantation area. Figure 1.2 shows the processes in nursery.

As a first step of nursery process, baby shoots are collected from existing sago plantations. The baby shoots are then cleaned by removing the body surface to prevent propagation of sago worm. After the cleaning process, baby shoots are arranged and placed on a bamboo raft for cultivation. The bamboo raft with baby shoots is left on the lagoon for three months.

Figure 1.2: Nursery process

After the three months cultivation, the baby shoots are transferred to another bamboo raft for second stage of cultivation (another three months). During this period, baby shoots are expected to have leaf. After this stage of cultivation, the baby shoots with leaf are then transferred into plantation bags for additional three more months. After nine months of cultivation process, the baby shoots are turned into young sago shoots with more leafs which are ready to sell or plant as sago palm in sago plantation area.

In sago plantation, huge amount of water is required to plant sago palms. Once the young sago palms are planted at sago plantation, sago palms will take approximately 9 – 12 years to complete its growth cycle (Flach, 1997; Singhal et. al., 2008; Bujang, 2008). In general, there are four stages in growth cycle which are "*Rosette stage*", "*Bole formation stage*", "*inflorescence stage*" and "*fruit ripening stage*" (Flach, 1997). During "*Rosette stage*", a total of 90 leaves are formed per palm and it normally takes approximately 45 months to complete. Then, the bole of palm elongates to maximum height and produces high amount of starch in "*Bole formation stage*". The starch is accumulated in the trunk and the palms are grown with approximately 24 leaves and 54 leaf scars at this stage. After 54 months, "*inflorescence stage*" is started. During this stage, the accumulated starch starts to decrease for seeds production for the next 12 months. This is then followed by last stage, "*fruit ripening stage*". In this stage, the fruit will be ripened and it consumes the starch accumulated in palm. Once the last stage is completed in 24 months, the sago palm will die.

In addition, sago palms produce baby and young shoots which are propagated beside the sago palm during the growth cycle. When the sago palm reaches the mature age, sago palm is then harvested and the young shoots continue to grow for future harvesting. Since the young shoots are produced every year, sago palms do not need to be re-planted and the harvesting activity can be held every year after the first 9 to 12 years of plantation. Figure 1.3 shows the young shoots propagated beside the sago palm.

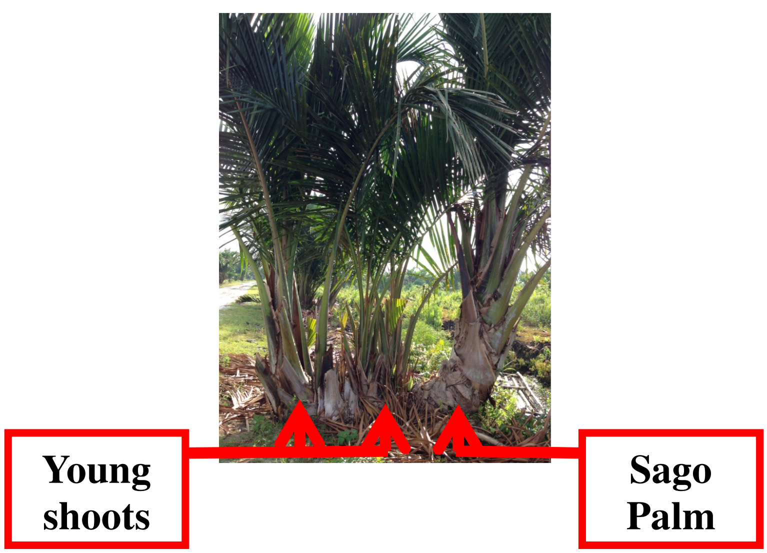

Figure 1.3: Young shoots propagated beside sago palm

1.3 Harvesting

Based on the current practise, the best harvesting time for sago palm is the beginning of "*inflorescence stage*" before "*fruit ripening stage*". Once the sago fruit is ripe, the accumulated starch in sago palm will be exhausted to produce sago seeds. This caused hollow shell and death to sago palm.

In harvesting process, the sago trunks are cut into logs, approximately one meter each. For a mature sago palm, about 6 – 12 of sago logs can be produced from a sago trunk (Flach, 1997; Bujang, 2008). These sago logs are then transported to sago mills for starch extraction via either road or river transportation. It is noted that sago biomass such as rachis and leaflet are generated during harvesting process. In current industrial practise, such biomass are used for mulching purpose in plantation area as shown in Figure 1.4.

Figure 1.4: Rachis and leaflet of sago palm

1.4 Sago Starch Extraction Process (SSEP)

Figure 1.5 shows the process block diagram of sago starch extraction process (SSEP). When sago logs arrived to sago mills, sago logs are first debarked. During debarking process, sago barks (Figure 1.6) is removed from sago logs and formed debarked sago logs (Figure 1.7). As shown in Figure 1.5, the debarked logs are then sent to rasping process to produce sago pith. Sago pith consists of fine and coarse fibres (Figure 1.8). To separate these fibres, sago pith is mixed with water at fibre separation and sieving processes. In this processes, sago wastewater, sago fibre and starch slurry are formed. The starch slurry is then further treated at starch water separation process to produced concentrated starch water. This starch water is further filtrated via packing filter to form wet flour. Meanwhile, sago wastewater is generated. The wet flour is then dried via hot air to produce high quality of sago flour (sago starch). Sago starch is then packed and sent to local customer via road transportation or exported to foreign customers via sea transportation.

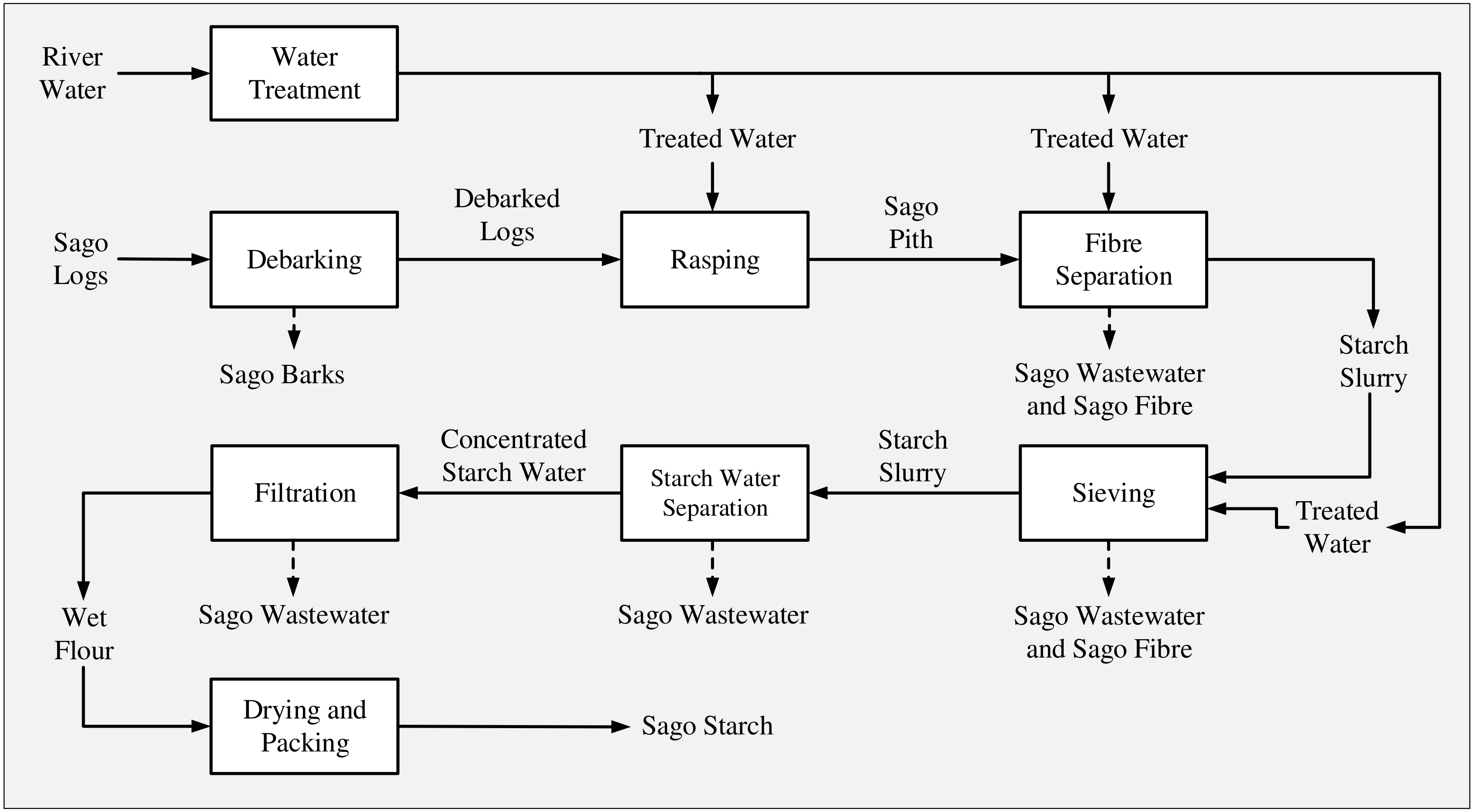

Figure 1.5: Process block diagram of sago starch extraction process (SSEP)

Figure 1.6: Sago barks

Figure 1.7: Debarked sago logs

Figure 1.8: Fine fibre (White Colour) and coarse fibre (Orange Colour)

In SSEP, approximate 160 – 200 kWh of electricity and 30 – 50 m^3 of water are consumed to produce one tonne of sago starch. Meanwhile, sago biomass such as sago barks, fibres and wastewater (see dotted lines in Figure 1.5) are generated.

According to Adeni et al. (2009), approximate 1.4 tonnes, 1.7 tonnes and 20 tonnes of sago barks, fibres and wastewater are generated, per tonne of sago starch produced. In current industrial practice, sago barks, which can be used as fuel source (Singhal et al., 2008) and raw materials for bioethanol production (Kannan et al., 2013), are used as flooring material in sago mill area. In case there are excess barks, the barks are then burnt off. Meanwhile, sago fibres and wastewater are discharged into nearest river without any treatment. As reported by Shim (1992), sago fibre is a lignocellulosic biomass which contains high percentage of starch (~ 65.7%). Thus, sago fibres can be converted into sugars and bioethanol (Vikineswary et al., 1994). Besides, it also could be converted into biosorbents (Kadirvelu et al., 2004), biogas (Aziz, 2002), animal feed and compost (Singhal et al., 2008), and biodegradable composite material (Lai et al., 2013). On the other hand, sago wastewater could be utilised as substrate for algae cultivation (Phang et al., 2000), biomethane generation (Nurleyna and Azhar, 2012), and bio-hydrogen generation (Hasyim et al., 2011). Although the sago biomass could be converted into various value-added products via different technologies, it is not being recovered from sago mills. Instead, they are being disposed to the environment. Therefore, this practice causes significant impacts to the environment.

1.5 Research Objectives

As discussed in the previous sections, due to the outdated practices of handling biomass in sago industry, severe environmental impacts, such as air and river pollutions are caused. In addition, raw materials (sago biomass), which can be converted into value-added products that beneficial to environmental and economic performance of sago industry, are wasted. These serious issues affect the sustainability of sago industry. Therefore, research objectives of this thesis are to improve the sustainability of sago industry by minimising the environmental impacts and maximising the overall economic performance of sago industry. In addition, strategies that improve sustainability of sago industry are developed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

As mentioned in Chapter 1, in order to produce sago starch and transfer to customers, several activities are involved and formed sago value chain. Therefore, the concept of value chain is first reviewed in this chapter. Due to the potential of sago biomass to be converted into various value-added products, as mentioned in Chapter 1, topics related to waste recovery, resource conservation and biomass conversion technologies are also reviewed in this chapter. Furthermore, a review of integrated biorefinery and interplant process integration is also presented in this chapter.

2.2 The Concept of Value Chain

The concept of value chain was first introduced by Porter (1998), who defined it as a set of primary and support activities used by a company to produce and deliver final products. The primary activities include inbound logistics, operations, outbound logistics, marketing and sales, as well as services after sales. In contrast, support activities include providing input material, manpower and technology via procurement, technology development and human resource management. The characteristics of the value chain of a company are dependent on its business strategies, and may differ between companies (Porter, 1998).

The concept of value chain was used as a cost analysis tool to assists decision-makers in pathway selection. This concept has been widely applied in various industries, such as, sugar (Higgins et al., 2007), meat and food processing (Graef et al., 2014; Sosnicki and Newman, 2010), medicine (Booker et al., 2012), automotive (Lind et al., 2012), aquaculture (Macfadyen et al., 2012; Ndanga et al., 2013; Ponte et al., 2014), cement production (De Souza and D'Agosto, 2013), poultry farming (Khaleda, 2013; Oguttu et al., 2014), wastewater treatment (Maaß et al., 2014), solar power generation (Olson, 2014; Sawhney et al., 2015), etc. However, application of this value chain concept is missing for sago industry in previous research work. Therefore, it is important to extend this concept to sago value chain as shown in Figure 1.1 for pathway selection as sago plantations are located in different places; sago starch can be produced in different sago mills and can be delivered to different customers via different ports.

On the other hand, due to the growing global concern for sustainable development, the concept of value chain has been further extended in recent research works towards the development of sustainable value chains (O'Rourke, 2014). Life cycle assessment (LCA) method has been identified as one of the suitable methods for such development problems (Hellweg and Canals, 2014), although conventional LCA approaches are limited to providing a measure of the environmental impact associated with a functional unit of product. There have been recent efforts to extend LCA into full life cycle sustainability analysis by taking into account life cycle costing (LCC) and social life cycle assessment (SLCA) (Heijungs et al., 2013). In addition, different environmental footprints have been proposed to account for various sustainability aspects in an integrated manner through a composite index (De Benedetto and Klemeš, 2009). For instance, carbon footprint is considered in value chain analysis along with economic performance in iron and steel industry (Dahlström and Ekins, 2006) and the aluminium industry (Dahlström and Ekins, 2007). In addition, Rudenko et al. (2013) combined water footprint analysis (WFA) and value chain analysis (VCA) to analyse both water footprint and economic aspects of the cotton value chain. Apart from the abovementioned works, Steubing et al. (2014) developed a spatial model which was based on carbon footprint and economic aspects to identify the optimal technology configuration of the synthetic natural gas (SNG) value chain. A recent review by Čuček et al. (2012) describes various footprint analysis metrics for monitoring impacts on sustainability.

Other than environmental sustainability, risk assessment is also another important factor to be considered in value chains. Angelucci and Conforti (2010) analysed agricultural risk and management risk for the value chain of fruits, vegetable and spices, while Oguttu et al. (2014) assessed risk of food poisoning for poultry (ready-to-eat chicken) value chain. Most recently, Ramadhan et al. (2014) considered work-related and human casualties in determining an optimal pathway of palm-based products value chain via life cycle optimisation (LCO) approach. As shown in Ramadhan et al. (2014), a statistical work-related fatality indicator (De Benedetto and Klemeš, 2009) is adapted as the measure of work-related and human casualties. This indicator is used as workplace footprint (WPFP). The proposed approach is based on the concept of benchmarking risk to human life in new systems using statistical ratio of fatalities per unit of economic activity in existing industries (Viscusi, 2003).

Based on the literatures above, it is noted that different footprints (i.e., carbon, water, and workplace footprints) were considered in various industries value chain to increase respective industry's sustainability. However, none of the existing research literature focuses on development of a sustainable value chain for sago industry. In addition, as mentioned in Chapter 1, current practices of the activities of sago value chain causes various serious impacts to the environment and thus exposing both neighbouring communities as well as workers to hazards. Therefore, different footprints are important to be considered in environmental and risk assessments for synthesising a sustainable value chain. However, environmental and risk assessments considering different footprints is missing in synthesising of sustainable sago value chain via systematic approach. Therefore, this is one of the major research gaps to be addressed in this research field. On the other hand, it is noted that the environmental issues are mainly caused by improper management of sago biomass which could be converted into various value-added products as mentioned in Chapter 1. Hence, waste recovery topic is reviewed in following section.

2.3 Waste Recovery

Waste recovery is one of the important strategies to achieve environment-friendly production while also enhancing economic performance. To promote in-plant waste recovery, numerous research works have been conducted for waste recovery in different industries in past decades. For instance, wastes from industrial centrifugation of juices (Tripodo et al., 2004), soya cake from oil production (Mittal et al., 2005), orange waste from beverage industry (Rezzadori et al., 2012), biodegradable wastes from grain industry (Kliopova et al., 2013), waste heat from steel industry (Zhang et al., 2013), cork wastes from cork industry (Nunes et al., 2013), etc. Note that the wastes can be recovered and converted into value-added products (e.g., animal feed, bio-oil, charcoal, pectin, ethanol, adsorbent, renewable fuel, and etc.) to reduce environmental impacts and increase economic performance. Besides, recovery of copper and iron (Xie et al., 2009), solder and phenols (Zhou et al., 2011), tin (Jha et al., 2012) from semiconductor industry, zinc from zinc electroplating process (Diban et al., 2011), and aluminium scrap from aluminium manufacturing process (David and Kopac, 2013) have been conducted for reduction of the usage of raw material, minimisation of profit lost, as well as for safe disposal. Based on the literatures, waste recovery has been performed in various industries to minimise the waste generation and environmental issues. However, in current industry practices, sago biomass such as sago barks, fibres and wastewater generated in SSEP is not being recovered. Instead, sago barks are used as flooring material and sago fibres and wastewater are discharged to the river. Therefore, in order to reduce environmental impacts and increase economic performance of sago industry, sago biomass needs to be recovered.

2.4 Resource Conservation Networks (RCNs)

Resource conservation networks (RCNs), which involves material recovery activities, is one of the solutions to improve environmental sustainability and business sustainability. In past decades, numerous research works have been conducted for synthesis of resource conservation networks (RCNs) (El-Halwagi, 2006; Foo, 2012). A typical RCN involves elements of pre-treatment, material reuse/recycle, regeneration/interception, and waste treatment for final discharge (Ng et al., 2010). Via RCN, the consumption of fresh materials, discharge of wastes, and total operating cost can be reduced. Over the past decades, numerous of works for synthesis and design of RCN have been presented for water (e.g., Bagajewicz, 2000; Foo, 2009; Jeżowski, 2010), utility gas (e.g., Alves and Towler, 2002; Foo and Manan, 2006; Agrawal and Shenoy, 2006), and property-based RCNs (e.g., Shelley and El-Halwagi, 2000; Kazantzi and El-Halwagi, 2005; Ng et al., 2009d; Chen et al., 2011a). In general, the developed techniques can be classified into insight-based techniques and mathematical-based optimisation techniques as well as combined insight- and mathematical-based techniques (Foo, 2009).

As shown in the literature, many insight-based techniques have been developed for material reuse/recycle. For example, limiting composite curve (Wang and Smith, 1994a), source and demand composite curves (Dhole et al., 1996), water surplus diagram (Hallale, 2002), Material Recovery Pinch Diagram (MRPD) (El-Halwagi et al., 2003; Prakash and Shenoy, 2005), cascade analysis (Manan et al., 2004), source composite diagram and wastewater composite curve (Bandyopadhyay and Ghanekar, 2006), source composite curve (Bandyopadhyay, 2006), Material Surplus Composite Curve (MSCC) (Saw et al., 2011), etc., were developed for water recovery network. On the other hand, hydrogen surplus diagram (Alves and Towler, 2002), Gas Cascade Analysis (GCA) (Foo and Manan, 2006), hydrogen source diagram (Borges et al., 2012), network allocation diagram (Wan Alwi et al., 2009), etc., were developed for utility gas network.

On the other hand, a new concept of property-based RCN which is governed by functionalities and properties (e.g., pH, turbidity, toxicity, colour, reflectivity, etc.) were introduced (Shelley and El-Halwagi, 2000). In addition, various approaches were developed for targeting and design of property-based RCN. For instances, functionality-based holistic approach (El-Halwagi et al., 2004), pinch-based graphical targeting technique (Kazantzi and El-Halwagi, 2005), property surplus diagram and property cascade analysis techniques (Foo et al., 2006), etc.

Besides the reuse/recycle strategies, the insight-based techniques were also extended to regeneration reuse and recycle systems in RCNs for further recovery of the materials. For example, Kuo and Smith (1998) extended the use of limiting composite curve to determine the regeneration reuse and recycling opportunities as well as the number of regeneration and wastewater treatment units. Bai et al. (2007) and Feng et al. (2007) introduced a revised targeting procedure to target minimum flowrate of regeneration and fresh water, and to determine the optimum inlet concentration for regeneration by using concentration-mass load diagram. Bandyopadhyay and Cormos (2008) extended the source composite curve to minimise the usage of freshwater based on the concept of regeneration and recycling of wastewater. Ng et al. (2007c; 2008) extended the use of water cascade analysis (WCA) technique to locate the ultimate water targets for RCN with regeneration system.

Viewing the interaction of waste treatment in synthesising and designing of RCN, the insight-based techniques were further extended. For example, composite curve was extended to target the minimum inlet flowrate and operating cost of wastewater treatment (Wang and Smith, 1994b; Kuo and Smith, 1997). In addition, the composite curve was also extended to locate the type and number of treatment system. MRPD and WCA were then extended to target minimum water flowrate, minimum treatment flowrate, and minimum number of treatment unit (Ng et al., 2007a; 2007b). Later, source composite curve was extended to target the optimal wastewater treatment (Bandyopadhyay and Cormos, 2008).

Other than insight-based techniques, mathematical-based optimisation techniques also gained much attention from the research community. Early works of mathematical-based optimisation techniques for synthesis of water network is presented by Takama and his co-workers. Takama et al. (1980) presented a mathematical programming model to minimise the total cost of a petroleum refinery and later Takama et al. (1981) introduced a linear programming (LP) for water allocation problem. Generally, mathematical-based optimisation techniques can be classified into deterministic mathematical optimisation approaches and stochastic optimisation approaches. As shown in the literatures, deterministic optimisation approaches were developed to design water network with multiple contaminants (Doyle and Smith, 1997), water treatment network (Huang et al., 1999) and water utilisation systems (Bagajewicz and Savelski, 2001), etc. Besides, optimal wastewater reuse network (Yang et al., 2000), robust water reuse networks (Tan and Cruz, 2004), and integrated water systems (Karuppiah and Grossmann, 2006) were also synthesised via deterministic optimisation approaches. Recently, Chen and his co-workers adopted the deterministic optimisation approaches to synthesise RCNs in palm oil milling process via property integration (Chen et al., 2011b) and to synthesise RCNs with interception placement (Chen et al., 2011c). On the other hand, many stochastic optimisation approaches (e.g., Genetic Algorithm (GA), Random Search Optimisation (RSO), Particle Swarm Optimisation (PSO), etc.) have been used for synthesis of RCNs. For instance, GA were used to optimise water distribution system (Gupta et al., 1999), to design water usage and treatment network (Tsai and Chang, 2001), to analyse network for pulp and paper mills (Shafiei et al., 2004), to synthesise an optimal water network topology (Lavric et al., 2005), etc. Besides, RSO were used to design a water network (Poplewski and Jeżowski, 2005), to synthesise a water usage network and to solve the complex formulation of Mixed Integer Non-Linear Programming (MINLP) (Poplewski et al., 2011). PSO also gained good attention of research community to solve non-convex Non-Linear Problem (NLP) and MINLP problems (Luo et al., 2007), property integration problem (Hul et al., 2007b), and MINLP models problem for water network synthesis (Hul, et al., 2007c). In addition, PSO was also adopted to design industrial material reuse/recycle networks (Tan et al., 2008).

Note that the insight-based and mathematical-based optimisation techniques complement each other well. The insight-based techniques locate various network targets prior to detailed design. Meanwhile, the mathematical-based techniques addresses more complex system which takes multiple impurities (Bagajewicz et al., 2000; Dunn et al., 2001; Savelski and Bagajewicz, 2003), costs (Hul et al., 2007a; Poplewsk and Jeżowski, 2005), topological constraint (Hul et al., 2007b; Lavric et al., 2005;), and process constraint (Hul et al., 2007a; 2007b; Tan and Cruz, 2004) into consideration. To have both advantages of techniques, combined insight- and mathematical-based approaches were developed for RCNs synthesis. Ng et al. (2009a) developed an Automated Targeting approach based on the framework of

WCA technique. This approach is flexible in changing the objective function, either to minimise the water flowrate or to minimise cost. This Automated Targeting approach is able to locate minimum water flowrate and operating cost for a single-component RCN with direct reuse/recycle (Ng et al., 2009a), interception placement (Ng et al., 2009b; 2009c) and total RCN (Ng et al., 2010). A more detailed review and a state-of-the-art review of process integration techniques for RCNs synthesis were given in Bagajewicz (2000), Foo (2009), and Jeżowski (2010).

Based on the abovementioned previous works, it is noted that most of the previous approaches were mainly focused in minimising the usage of fresh resources, waste generation, and total operating cost of RCNs via material recovery. However, the recovery strategy used by previous developed approaches was mainly based on the quality and quantity of waste streams. In case where the quality of waste streams is same, the previous proposed approaches are not able to prioritise the waste streams for recovery. In order to address the limitation of the previous approaches, several prioritisation approaches were developed for waste recovery. For instance, the waste stream prioritisation matrix ranks alternatives based on various criteria (i.e. health and safety risk, material value, existing and potential market, job creation, litter abatement, etc.) (NWMSI, 2005) was developed. Besides, Wang and Gaustad (2012) developed a weighted sum model based on economic value, energy saving potential, and eco-toxicity. Although multiple criteria are considered in these previous prioritisation approaches, neither approach considered the cost of waste streams which reflect the wasted inputs to generate the waste streams. In case where the costs are taken into consideration for RCNs synthesis, different recovery strategy might be determined. It is noted that different recovery strategy will leads to different economic performance of an industry process. However, this concern did not be considered in most of the previous works of RCN synthesis. Furthermore, it is also noted that most of the previous RCNs synthesis approaches did not incorporated with the prioritisation concept for waste recovery. Therefore, in order to address the limitations of previous approaches, a novel prioritisation-based mathematical approach is vital to be developed for simultaneous synthesis of RCNs and industrial processes. In this thesis, integrated total water network and sago starch extraction process (SSEP) is synthesised simultaneously based on prioritisation-based mathematical approach.

2.5 Material Flow Cost Accounting (MFCA)

Material Flow Cost Accounting (MFCA) is a tool of Environmental Management Accounting (EMA) (Fakoya and Van Der Poll, 2013) that focuses on imputing cost shares to waste streams (Kokubu et al., 2009). The ultimate purpose of MFCA is to mitigate environmental issues and concurrently improve economic performance (Onishi et al., 2008). This concept has been successfully used in numerous industrial applications, such as lens manufacturing (Anjo, 2003; Schmidt and Nakajima, 2013); chemical, healthcare and pharmaceutical production (Kokubu et al., 2009); electronics manufacturing (Kokubu and Tachikawa, 2013); optoelectronic and electric power industry (Trappey et al., 2013); automotive industry (Kokubu et al., 2009); ceramic tiles production (Hyršlová et al., 2011); heavy machinery production (Tang and Takakuwa, 2012); and the brewery industry (Fakoya and Van Der Poll, 2013). These cases demonstrate that MFCA helps in improving overall economic performance of companies.

MFCA traces input and output material flows in both physical and monetary units so that the information of waste cost can be captured precisely (Jasch, 2009). In MFCA, waste is treated as a by-product. The main consequence of this assumption is that the manufacturing cost is not only used to produce the desired products, but also the undesired by-products (wastes). The latter is thus said to possessing part of the processing cost of all upstream processing steps. According to Strobel and Redmann (2002), there are four types of costs (i.e. material, system, energy and waste management costs) taken into consideration under the concept of MFCA. These costs are distributed to wastes and products as shown in Figure 2.1 (Kokubu and Tachikawa, 2013). The distribution is based on the attribution of specific activities to the generation of product and waste streams.

As shown in Figure 2.1, the material, system and energy costs are attributed to product and waste according to the material distribution percentages (70% of product and 30% of waste). On the other hand, all the waste management costs are 100% attributed to waste (Kokubu and Tachikawa, 2013). Following with the concept of MFCA, every individual waste stream has an attributed cost which reflects the cumulative effort invested through successive processing steps to generate these streams. This concept makes the attributed cost as one of the important criterion to be considered in prioritisation of waste streams. Hence, the concept of MFCA could be incorporated with prioritisation-based approach to prioritise the waste streams to be recovered.

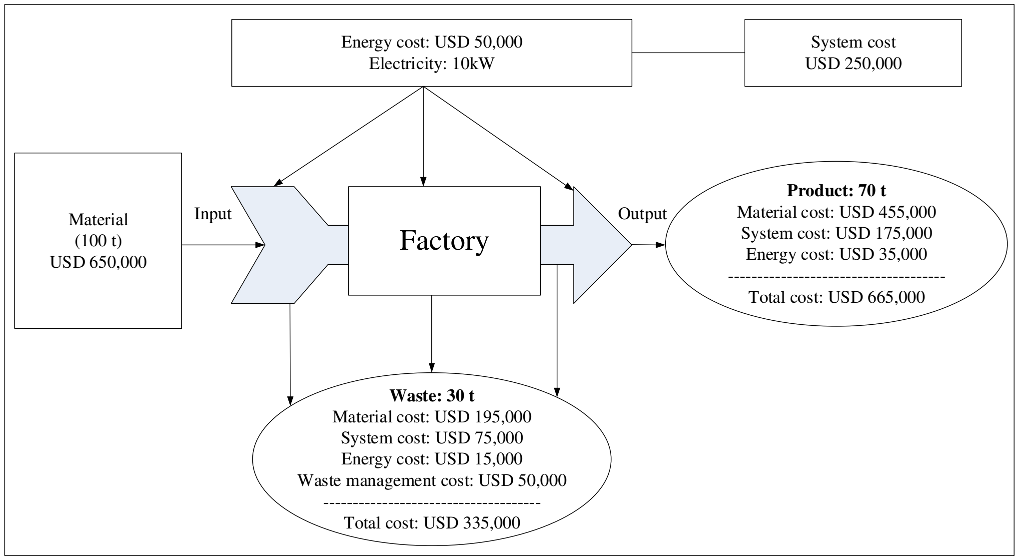

Figure 2.1: Material flow cost accounting (MFCA) evaluation in monetary unit (Kokubu and Tachikawa, 2013)

As mentioned in Chapter 1, there are three types of waste streams could be recovered from sago starch extraction process (SSEP), which are sago barks, fibres, and wastewater. According to Singhal et al. (2008), sago barks and fibres are one of the alternative energy sources for electricity generation as it consists of solid lignin structures that are suitable for combustion for energy production. In addition, huge consumption of electricity (~160 – 200 kWh/t of sago starch) and energy is required in SSEP to produce sago starch. Therefore, the efficiency of energy production and energy recovery in the sago industry needs significant improvement so that a better energy, economic, and environmental performance can be achieved. Therefore, biomass-based combined heat and power (CHP) systems, which convert biomasses into energy (heat and power), is subsequently reviewed in following section and followed by the review of conversion technologies for bioethanol.

2.6 Biomass-based Combined Heat and Power (CHP) Systems

Combined heat and power (CHP) system is a cogeneration system that generates heat and power simultaneously using single primary energy source. In previous research works, various configurations of biomass-based CHP system, which using biomass as feedstock, were introduced and reported to convert biomass into heat and power. For instance, downdraft gasifier-based CHP system (Huang et al., 2013), biomass gasification based combined cycle CHP system (Sadhukhan et al., 2009), natural gas combined cycle combined heat and power (NGCC-CHP) (Klaassen and Patel, 2013; Marbe et al., 2006), micro CHP system (Ren and Gao, 2010; TeymouriHamzehkolaei and Sattari, 2011), etc. Besides, the biomass-based CHP system has been applied in different industries. For example, glasshouses (Moreton and Rowley, 2012), sawmill (Anderson and Toffolo, 2013), wood (Kohl et al., 2013), etc. Based on the literatures, it is noted that CHP system is a well-established system to convert biomass into heat and power.

Conventionally, such system consists of four major components which are biomass receiving and preparation, biomass conversion, power generation and heat recovery (Huang et al., 2013). Besides, biomass CHP system can be categorised into two types which is boiler-based CHP system and gasifier-based CHP system. Boiler can be classified into oil-fired, gas-fired, coal-fired, or solid fuel-fired boilers (Oland, 2002). Biomass boiler is categorised as solid fuel-fired boiler (Chau et al., 2009). Besides, boiler also can be classified into fire-tube and water-tube boiler (Spring, 1981). In a fire-tube boiler, the combusted heat is running through the tube to heat up the surrounding fluid (water). In contrast, the water is running through the tubes in water-tube boiler. The water in the tube is heated up by the surrounding combusted heat (Spring, 1981). In general, biomass boiler is using water-tube type and it is connected with a close-loop water system (Spring, 1981). Since boiler–based CHP system has much simpler design, it requires less capital cost, operating cost and maintenance cost (Huang et al., 2013; Sotirios and Andreas, 2007). The main concern about boiler-based CHP systems is that the exhaust gas quality may not be monitored. In most CHP systems, the usual pollutants are dust and particulates escaping from char and ash components of biomass and some volatile organic compounds such as phenolic compounds, known as tar (Sadhukhan et al., 2009). Though an activated carbon based gas filter may be used to capture some of these pollutants, the temperature, pressure and the flue gas velocity may not mitigate all the pollutants from escaping to the atmosphere.

On the other hand, gasifiers are available in fixed bed, moving bed, fluidised bed and entrained bed configurations (Bridgwater et al., 2002). The flow pattern of fixed and moving bed can be updraft, downdraft or crossdraft (Sadhukhan et al., 2014). The fixed and moving bed gasifiers need less oxidant, but they require high maintenance cost, produce significant amount of tar and oil and have poor mixing and heat transfer as well as higher risk of agglomeration. In contrast, the fluidised bed gasifier has uniform temperature distribution, good mixing, lower risk of agglomeration and produce less tar and oil (Sadhukhan et al., 2009). However, considerable amount of char could be recycling in the gasifier reactor. Apart from this, gasifier-based CHP system can produce a combustible gas consisting of carbon monoxide, hydrogen and methane from majority of the carbon and hydrogen content in biomass (Huang et al., 2013) that can be treated and cleaned (Sadhukhan et al., 2009). Hence, gasifier-based CHP system is considered for more sustainable development of industries. A detailed review of cogeneration technology was reported by Onovwiona and Ugursal (2006). Besides, Obernberger et al. (2003), Obernberger and Thek (2008) and Haslinger and Friedl (2010) also reported the state-of-the-art and future developments of biomass-based CHP system. Since both types of biomass CHP systems has its advantages and disadvantages, techno-economic performance and environmental performance of both systems is vital to be examined to determine the most feasible and viable systems for an industry in CHP generation.

According to literatures, CHP system is a more efficient and environmental friendly compared to conventional generation systems (Erdem et al., 2007; Basu, 2013; Roy et al., 2014). It reduces total fossil fuel consumption and greenhouse gas emission without compromising the quality and reliability of the energy supply to consumers. Besides, Roy et al. (2014) reported that CHP system is an efficient and reliable method for power generation; it can greatly increase the operational efficiency and decrease energy cost. Therefore, it is vital to be implemented to improve the sustainability of an industry. However, the biomass-based CHP system is yet to be implemented in sago industry.

On the other hand, numerous previous research works were also conducted to evaluate techno-economic performance of biomass-based CHP system for particular biomass, such as, willow chips and miscanthus (Huang et al., 2013), palm-based biomass (Andiappan et al., 2014), straws (Sadhukhan et al., 2009), poplar wood and oil palm empty fruit bunch (Ng and Sadhukhan, 2011a), olive stone (Celma et al., 2013), woods (Morita et al., 2004), wood pellet and wood residue (Chau et al., 2009), etc. These previous works succeed to show the feasibility and viability of biomass-based CHP system with such particular biomass. In order to encourage investors to invest biomass-based CHP system in Malaysia, it is vital to evaluate the techno-economic and environmental performance of biomass-based CHP systems in Malaysia context so that its feasibility and viability can be examined. However, none of the previous research works has been conducted to evaluate the technical and economic feasibility of CHP system using sago biomass as feedstock. Therefore, it is vital to address this research gaps.

2.7 Biomass Conversion Technologies for Bioethanol Production

Bioethanol is one of the renewable energy and can be used as an alternative fuel to replace fossil fuels. As current practice in Brazil, bioethanol can be blended with gasoline to reduce the usage of gasoline and fossil fuel. Based on the successful practices in Brazil, it proves that the conversion technology of biomass into bioethanol is a well-established technology. In addition, environmental impacts such as emission of carbon dioxide (CO_2) can be reduced by reduction of dependency of fossil fuels. Therefore, production of bioethanol is important.

Biomass is one of the promising alternative energy sources that can be converted into bioethanol. It is a lignocellulosic material which comprising of cellulose, hemicellulose and lignin, In order to convert lignocellulosic material into bioethanol, biochemical conversion technology is a more favoured conversion technologies compared to thermochemical technology as it has easier process design, required lower capital cost and operating cost (Dutta and Phillips, 2009; Humbird et al., 2011; Phillips et al., 2007). Biochemical conversion technology composes of pre-treatment, hydrolysis, fermentation, and ethanol recovery processes (Bharathiraja et al., 2014, Humbird et al., 2011). Note that, there are several types of pre-treatment in biochemical conversion technology, for instances, acid-based pre-treatment (Humbird et al., 2011; Mathew et al., 2011; Tucker et al., 2004), alkaline-based pre-treatment (Harun et al., 2011; Zhu et al., 2006), and hydrothermal-based pre-treatment (Boussarsar et al., 2009; Oliveira et al., 2014; Saha et al., 2013). During the pre-treatment process, the structure of biomass is broke down to release cellulose and hemicellulose. The cellulose and hemicellulose are then depolymerised in hydrolysis process to produce respective free sugars (glucose and xylose). This is followed by fermentation process where the free sugars are converted into ethanol. Lastly, the produced ethanol is recovered via recovery process such as distillation process (Alzate, et al., 2006; Bharathiraja et al., 2014).

Note that, biomass is a cheaper substrate if compared to others resources. Besides, it is also a renewable and environmental friendly material (Bharathiraja et al., 2014). Due to these reasons biomass has been utilised as raw material for bioethanol production in the past decades. For instances, biomass such as wheat straw (Martinez-Hernandez et al., 2013; Zhu et al., 2006), maize (Demirbas et al., 2003), wet distillers grain (Tucker et al., 2004), rice straw (Karimis et al., 2006), corn stover (Saha et al., 2013), oilseed rape straw (Mathew et al., 2011), sorghum baggase, (Heredia-Olea et al., 2012), etc. have been utilised for sugar and ethanol production. In fact, sago biomass is also one of the lignocellulosic material that could be converted into bioethanol (Adeni et al., 2013; Kannan et al., 2013; Thangavelu et al., 2014). However, not many research works considered sago biomass as raw material for bioethanol production. Instead, different works were presented on production of ethanol from sago starch in the past decades. For instance, Kim et al. (1992) studied simultaneous saccharification fermentation (SSF) for ethanol production in batch and semi-batch modes using sago starch as raw material, Amyloglucosidase as an enzyme, and Zymomonas mobilis as a bacterium. Later, the study was extended to continuous process using free, immobilised or co-immobilised enzyme and cells by Kim and Rhee (1993). Meanwhile, Aziz et al. (2001) investigated the effect of carbon to nitrogen (C/N) ratio and initial sago starch concentration on the performance of direct fermentation of sago starch into bioethanol by recombinant yeast, Saccharomyces cerevisiae YKU 131. Besides, the effects of temperature, pH and time of fermentation were also investigated on SSF using sago starch as raw material and with different enzymes such as glucoamylase and Symomonas mobilis ZM4 (Ratnam et al., 2003), and Amyloglucosidase and Zymomonas mobilis MTCC 92 (Bandaru et al., 2006).

Apart from the abovementioned works, performance of a microwave assisted bioethanol production from sago starch has also been investigated (Saifuddin and Husain, 2011). A series of studies on hydrolysis of sago starch for ethanol fermentation was also conducted by Sunaryanto et al. (2013). Note that sago starch is one of the important foods for human as it contains high amount of carbohydrate. In order to avoid shortage of food, sago starch should not be converted into bioethanol. Instead, to replace fossil fuel while to reduce environmental pollutants, sago biomass could be recovered and converted into bioethanol. Although sago biomass could be converted into bioethanol via hydrolysis and fermentation process as reported by Adeni et al. (2013), Kannan et al. (2013), and Thangavelu et al. (2014), sago biomass is not being recovered by sago mills owner in current industrial practices. Instead, it is being disposed to the environment and causes severe environmental issues and wastage of valuable energy as mentioned in Chapter 1. Therefore, as mentioned earlier, sago biomass is vital to be recovered and converted into bioethanol to have more sustainable sago industry. In other words, sago-based bioethanol plant (SBP) needs to be implemented in sago industry to increase its sustainability. However, SBP is yet to be implemented in sago industry and hence techno-economic performance of SBP is vital to be evaluated to analyse its feasibility and viability. This is one of the main research gaps of sago industry.

In line with the global efforts in sustainable development, the concept of integrated biorefinery is important to be adopted in an industry for more sustainable productions, competitive economic operation and environmental performance. Therefore, related topics such as integrated biorefinery and interplant process integration are reviewed in following sections.

2.8 Integrated Biorefinery

According to the definition given by Kamm et al. (1998), biorefinery is "*a complex system of sustainable, environment- and resources-friendly technologies for the comprehensive utilisation and the exploitation of biological raw materials (biomass)*". In order to increase the overall energy and mass efficiency of a biorefinery, the concept of integrated biorefinery has been proposed (Fernando et al., 2006). Integrated biorefinery integrates multiple biomass conversion processes (biological, physical and thermo-chemical) or technologies to convert biomasses into a wide range of products. The concept flow of integrated biorefinery is shown in Figure 2.2.

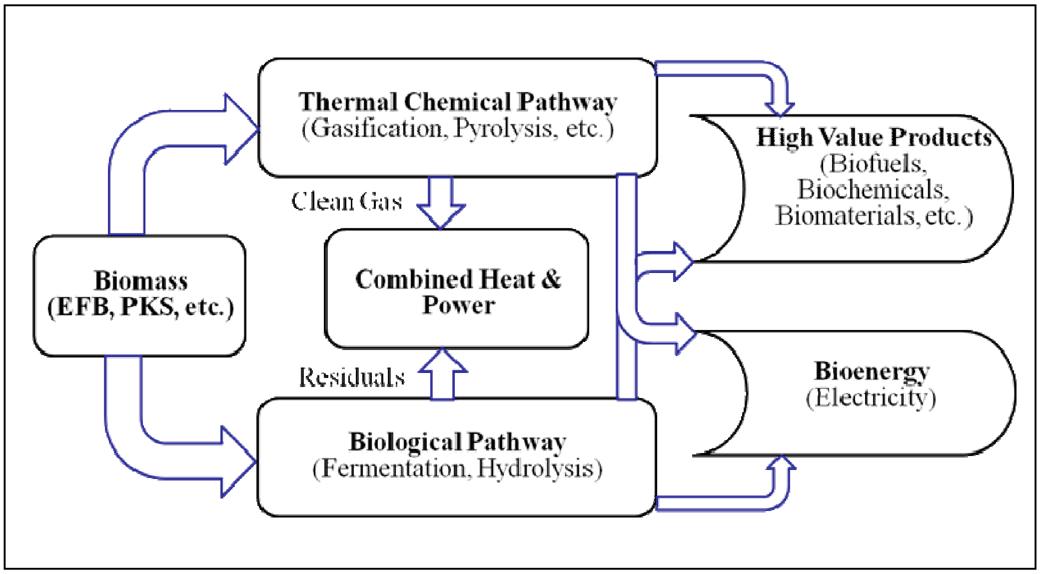

Figure 2.2: Integrated biorefinery concept flow (Ng, 2014)

As shown in Figure 2.2, two platforms (biological and thermal chemical) are integrated with a combined heat and power (CHP) system to produce bioenergy and high value products. The biomass is fed into two different platforms and converted into value added products (e.g., biofuel, biochemical, biomaterial, etc.) and bioenergy (e.g., electricity, etc.). Meanwhile, clean gas and residuals are generated from the platforms can then be supplied to CHP system to produce heat and power, and supplied back to the pathways. Additional bioenergy can be exported to the grid as product. In order to increase sustainability of sago industry, integrated sago-based biorefinery (SBB), which composes of sago starch extraction plant (SSEP), sago-based CHP system, sago-based bioethanol plant (SBP), and wastewater treatment plant (WWTP), is important to be developed in sago industry. In order to determine the feasibility and viability of integrated SBB, techno-economic performance and environmental performance of integrated SBB is vital to be evaluated. This is an initial step to encourage investors to invest in sago industry so that integrated SBB can be implemented and subsequently increase the sustainability of sago industry.

2.9 Interplant Process Integration

Process integration (PI) techniques are well established approaches for reduction of energy consumption in industrial plants (Linnhoff et al., 1982). Such reductions have also been linked to consequent reduction of emissions in total sites (TS) comprised of multiple plants (Dhole and Linnhoff, 1993). Furthermore, four decades of development have seen parallel development of process integration tools such as pinch analysis and mathematical programming methods (Klemeš and Kravanja, 2013).

On the other hand, in recent year, symbiotic strategies have gained good attention from research community in increasing sustainability of an industry. This concept, industrial symbiosis (IS) emphasises mutually beneficial exchanges of process wastes among different plants, so that the resources demand and the generation of wastes can be reduced. This concept originates from the concept of industrial ecology (IE) which emerged as a framework for improving the sustainability of industrial systems by emulating highly cyclical flows found in natural ecosystems (Frosch and Gallopoulos, 1989). IE focused on the potential benefits (i.e., reduction of waste generation, raw materials and energy consumption, etc.) of symbiotic interaction among various companies (Korhonen, 2001). Nowadays, there are clear attempts to induce symbiosis programs by providing close proximity and shared services to plants within the eco-industrial parks (EIP). Besides, Chertow (2007) noted that initial exchange of key industrial utilities such as energy or water often serves as a vital initial step towards more comprehensive IS networks. Thus, there are clear similarities with the TS concept used in PI, which involves resource recovery and utilities sharing in clusters of process plants. The initial concept focused on heat integration to achieve optimal reductions in fuel consumption and CO_2 emissions (Dhole and Linnhoff, 1993). In addition to the pinch analysis approach, mathematical programming has also been proposed for TS integration (Marechal and Kalitventzeff, 1998). PI techniques have since been developed further to facilitate such sharing of utilities in EIPs. For example, Chen and Lin (2012) recently developed a mathematical programming approach for heat integration between industrial plants. Further developments in TS heat integration have focused on retrofitting (Liew et al., 2015) and process modifications (Chew et al., 2015) to optimise savings. Two recent book chapters describe the state-of-the art of total site methodology with emphasis on heat integration (Perry, 2013) and water integration (Kim, 2013), while a third chapter in the same volume describes successful industrial applications (Matsuda, 2013).

It is noted that the inherent conflicts of interest among potential partners is one of the main challenges to the emergence of IS. As noted by Jackson and Clift (1998), every firm is a “self-interested maximiser of individual profit” who might not necessarily be interested in optimising the benefits for the entire system. By comparison, most optimisation frameworks within PI, including TS methodology, implicitly assume the existence of a single decision-maker. Thus, an alternative modelling approach is necessary to model such multi-agent behaviour. Game theory has long been used as a mathematical framework to model the behaviour of multiple agents (i.e., decision-makers) with potentially conflicting interests in various domains (von Neumann and Morgenstern, 1944). Game theory based approaches have also been developed within the context of IS and IE. The earliest reported work used a matrix game representation using emergy as a measure of sustainability (Lou et al., 2004). Chew et al. (2009) later proposed a matrix game approach for the establishment of water networks in an EIP. A static Stackelberg game model was formulated as a bi-level mathematical program for modelling government-industry interactions in EIPs using both direct exchanges among plants (Aviso et al., 2010) and intermediate hubs through which exchanges are channelled (Tan et al., 2011). The latter models were solved heuristically via fuzzy optimisation. An alternative approach based on inverse optimisation was also proposed by Tan and Aviso (2012). Later work recognised the natural significance of cooperation among partners in an IS scheme (Piluso and Huang, 2009). For instance, Chew et al. (2011) demonstrated how incentives can be used to induce cooperation to yield Pareto optimal solutions in an EIP.

Furthermore, fuzzy optimisation techniques have been proposed to approximate game-theoretic approaches. Aviso et al. (2010b) proposed such a model for water integration in an EIP; an extension of this approach that used emergy as a sustainability index was later developed by Taskhiri et al. (2011). A fuzzy disjunctive programming model has been proposed for the optimal synthesis of an integrated biomass complex, where each plant has a priori targets and disjunctions arise due to the option to not participate in interplant integration (Ng et al., 2014). A fuzzy model for biomass allocation in an EIP for energy recovery purposes was also proposed by Taskhiri et al. (2015). These models all assume that each decision-maker has predefined goals prior to the start of negotiations with potential partners in an EIP; the optimisation process merely seeks to determine an equitable compromise. On the other hand, an alternative approach is to pool total profits or savings arising from an IS program, and subsequently allocating the benefits among the partners in the EIP. For example, multiple plants can share a centralised utility system for provision of energy (Liew et al., 2013) or water (Chew et al., 2008); in such cases, it is often unclear how costs and benefits of cooperation should be shared. Cooperative game theory can be used to provide a rational basis for such decisions. Basically, there are many concepts can be used to solve cooperative games. For instances, The von Neumann stable set, the core, the kernel, the Shapley value, the nucleolus, and the Nash bargaining solution are the most common concept (Maali, 2009). Recently, Hiete et al. (2012) proposed the use of the Shapley value (Shapley, 1953) as a rational basis for profit-sharing for the interplant heat integration case. Such rational basis for profit-sharing is important for sago industry. As suggested in previous section (Section 2.8), SBB could be formed to increase the sustainability of sago industry. Hence, it is vital to encourage the plants owners (i.e., SSEP, CHP system, WWTP, and SBP) to participate. As first step of the encouragement, determination of deserve benefits of each plants participating in integrated SBB is paramount of importance since every plant is a "self-interested maximiser of individual profit" (Jackson and Clift, 1998). Therefore, cooperative game theory could be adopted to allocate fairly and rationally the deserve benefits of each party in integrated SBB. Noted that, a mathematical linear programming model which is based on the idea of the core have been introduced by Maali (2009) to solve cooperative games. In this model, a multi-objective approach that including the importance weights of the players is used. According to Maali (2009), it is a very simple approach and its solution is always Pareto optimal. Hence, this approach is adopted in this thesis to allocate the deserve benefits of each party in integrated SBB. Since this approach is introduced by Maali, the name of 'Maali's method' is used in this thesis.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

In this chapter, research gaps are first determined in Section 3.2. This is followed by research scopes of this thesis in Section 3.3. Lastly, a systematic research methodology is presented in Section 3.4.

3.2 Research Gaps

Based on the above literature review in Chapter 2, several research gaps are determined in this thesis, which are listed as below:

1) Systematic approach considering environmental and risk assessments in synthesising of sustainable sago value chain has not been developed.
2) Prioritisation approach for waste recovery in the case where the quality and quantity of waste streams are same is yet to be developed.
3) A systematic approach for simultaneous synthesis of resources conservation networks (RCNs) and industrial processes is needed to be developed.

4) Techno-economic performance evaluation for biomass-based CHP system has not been performed for sago industry.
5) Techno-economic performance evaluation for integrated sago-based bioethanol plant (SBP) which using sago biomass as raw materials has not been conducted.
6) Deserve benefits of each plant participating in integrated sago-based biorefinery (SBB) is yet to be determined via a rational and defensible mathematical approach that based on cooperative game theory.

To address the research gaps as abovementioned, research scopes are set in following section.

3.3 Research Scopes

In order to address the research gaps as determined in Chapter 2, followings research scopes are identified:

1) Development of Fuzzy Multi-Footprint Optimisation (FMFO) approach, which considers carbon, water, and workplace footprints as well as economic performance simultaneously, to synthesise an optimum sago value chain.
2) Development of Material Flow Cost Accounting (MFCA)–based approach, which considers industrial costs, for prioritisation of waste recovery.

3) Extension of MFCA-based prioritisation approach to eMFCA-based prioritisation approach for integrated design of total resource conservation networks (RCNs) and sago industrial processes.
4) Evaluation of techno-economic performance and environmental performance of sago-based combined heat and power (CHP) systems to investigate its technical and economical feasibility.
5) Evaluation of techno-economic and environmental performance of integrated sago-based biorefinery (SBB) to investigate its technical and economical feasibility.
6) Optimal allocation of benefits of each plant in integrated sago-based biorefinery (SBB) via an optimisation-based cooperative game approach.

3.4 Research Methodology

The research methodology of this thesis is summarised in Figure 3.1:

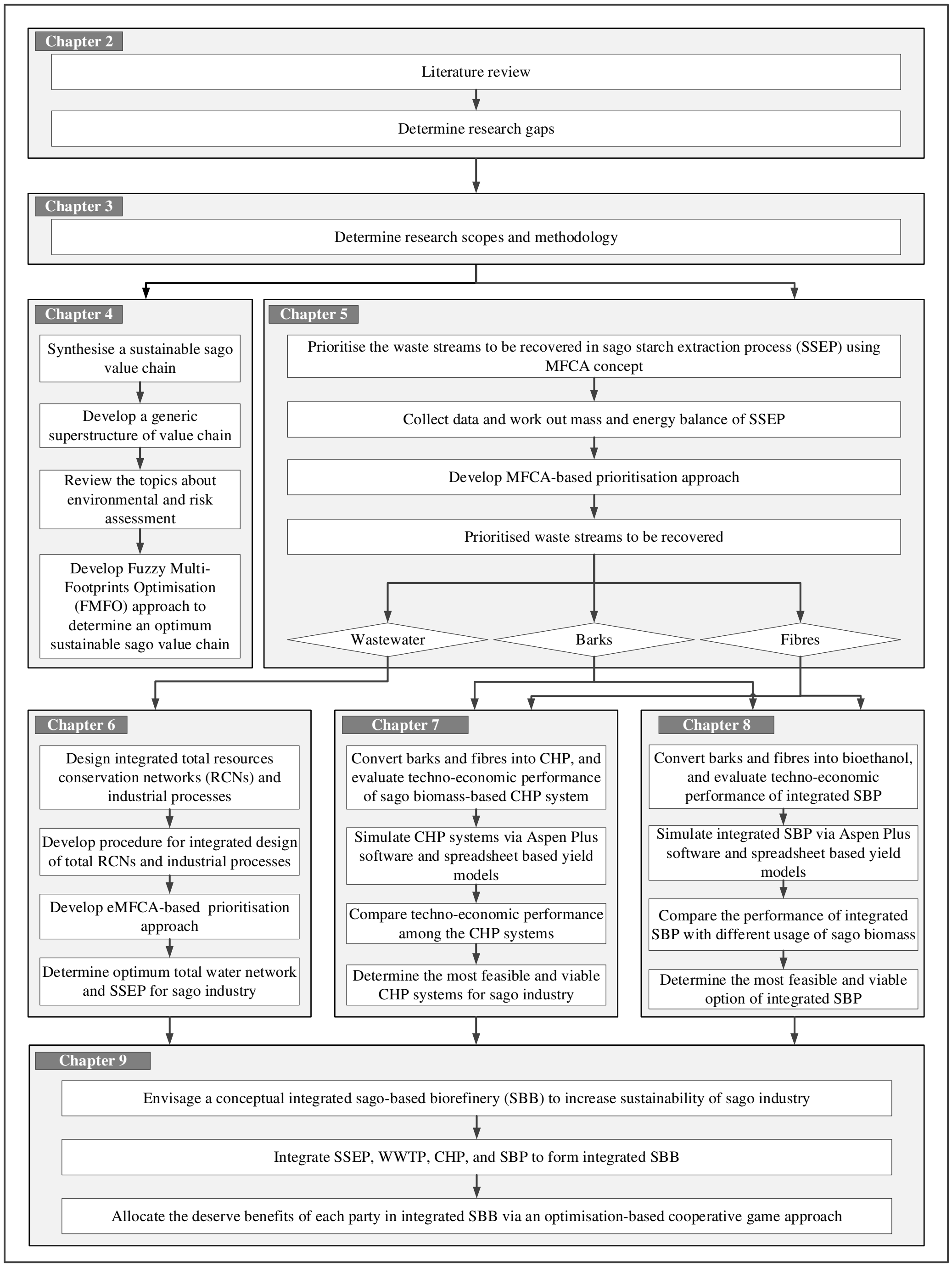

Figure 3.1: Research methodology

As shown in Figure 3.1, literature review is first conducted in Chapter 2 to determine the research gaps of this thesis. Then, it is followed by this chapter (Chapter 3 –

Research Methodology) to present the methodology which is used to cover the scopes listed in Section 3.2.

In Chapter 4, Fuzzy Multi-Footprint Optimisation (FMFO) approach, is developed to synthesise a sustainable sago value chain. The proposed FMFO approach considers carbon footprint, water footprint, and workplace footprint as well as economic performance in synthesising a sustainable sago value chain. To synthesise a sustainable sago value chain via FMFO approach, a generic superstructure of value chain that consists of different pathway to deliver sago logs from various plantations to different sago mills for starch production and deliver sago starch to different customers via different ports is first developed. Based on the developed superstructure, a mathematical model of FMFO approach is developed to determine an optimum sustainable sago value chain.

In Chapter 5, a novel prioritisation approach which is based on Material Flow Cost Accounting (MFCA) concept is presented for waste recovery. In order to prioritise the waste stream to be recovered in sago starch extraction process (SSEP) via MFCA-based prioritisation approach, all related data (e.g., mass flowrate of each stream, energy consumption of each processing step, etc.) is first collected to work out the mass and energy balance of SSEP. Then, a mathematical model of MFCA-based prioritisation approach is developed to prioritise the waste streams to be recovered.

In Chapter 6, MFCA-based prioritisation approach developed in Chapter 5 is extended to synthesise resource conservation networks (RCNs) and industrial processes simultaneously. The extended MFCA (eMFCA)-based prioritisation approach considers industrial costs, quality and quantity of waste streams for resources recovery. In order to synthesise RCNs and industrial processes simultaneously, a procedure of integrated design is first developed. Then, a mathematical model of eMFCA-based prioritisation approach is developed. Via the developed eMFCA-based prioritisation approach, an optimum total water network and SSEP of sago industry is determined.

In Chapter 7, sago barks and fibres are recovered and converted into combined heat and power (CHP) via biomass-based CHP systems. In order to examine the feasibility and viability of the biomass-based CHP systems in Malaysia context, technical and economic performance as well as environmental performance of the biomass-based CHP systems is evaluated. To evaluate the techno-economic and environmental performance, the CHP systems are simulated via Aspen Plus software and spreadsheet based yield models. Then, the performance are compared among the CHP systems to determine the most feasible and viable configuration of CHP system for sago industry of Malaysia.

In Chapter 8, sago barks and fibres are recovered for bioethanol production in integrated sago-based biorefinery (SBB) which composed of SSEP, CHP system, wastewater treatment plant (WWTP), and sago-based bioethanol plant (SBP). Similar to Chapter 7, Aspen Plus software and spreadsheet based yield models are used to simulate the integrated SBB. Then, techno-economic performance of integrated SBB as well as its environmental performance is evaluated in Malaysia context. The techno-economic and environmental performance is subsequently compared to determine the most feasible and viable option of integrated SBB for sago industry of Malaysia.

In Chapter 9, a conceptual integrated SBB is envisaged to improve sustainability of sago industry. In order to locate systematically the deserve benefits of each party in integrated SBB, an optimisation-based cooperative game approach is proposed.

Lastly, conclusions and future works are given in the last chapter of this thesis (Chapter 10).

CHAPTER 4

FUZZY MULTI-FOOTPRINT OPTIMISATION (FMFO) FOR SYNTHESIS OF A SUSTAINABLE VALUE CHAIN: MALAYSIAN SAGO INDUSTRY

4.1 Introduction

In line with the global efforts in sustainable development, sustainable value chain is needed to ensure the industry to be competitive in economic operation, environmental and social performance. As shown in Figure 4.1, sustainable development includes three interconnected domains which are economic, environmental, and social.

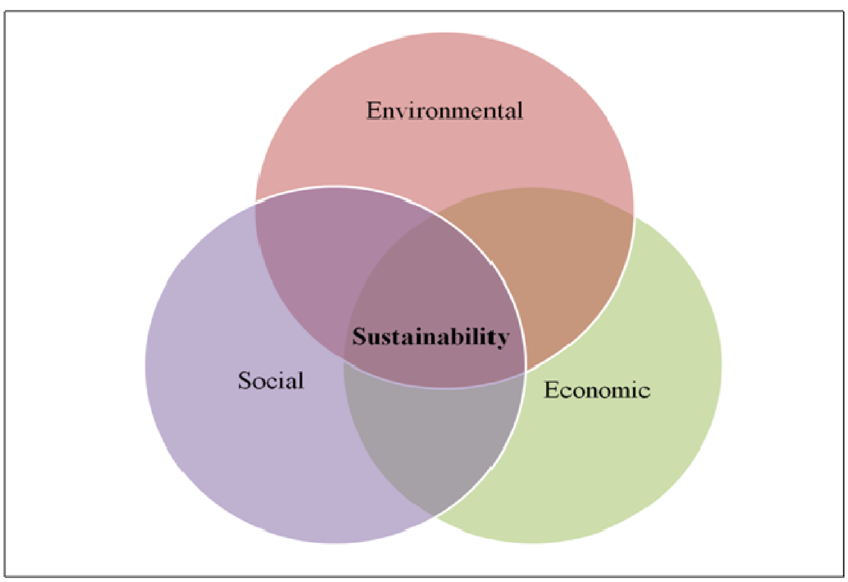

Figure 4.1: Venn diagram of sustainability (Adams, 2006)

Therefore, in order to develop a sustainable value chain for sago industry, all three domains should be considered simultaneously. In this chapter, water footprint (WFP) and carbon footprint (CFP) are used as the indicators of environmental impacts. Meanwhile, workplace footprint (WPFP), which measures work-related casualties, is developed in the work and used as the measure of social impacts. Economic performance of sago value chain is evaluated. In order to trade-off the economic performance of the value chain with those footprints, a multi-objective optimisation approach, fuzzy optimisation approach is adapted. In this chapter, Fuzzy Multi-Footprint Optimisation (FMFO) approach is presented. An industrial sago case study is then solved to illustrate the application of the proposed model.

4.2 Environmental and Risk Assessment

As mentioned in Chapter 1, sago starch is one of the main carbohydrate sources in many South East Asian countries and Papua New Guinea. To produce sago starch, several activities such as plantation, harvesting, starch processing and road transportation are involved in the sago value chain. A large amount of freshwater (about 30 – 50 m^3) is required to produce one ton of sago starch in sago value chain especially in activities sago plantation and starch processing. Meanwhile, a massive amount of wastewater (more than 20 m^3 per ton of sago starch produced) is generated during starch processing. The resulting wastewater is often discharged to the environment without proper treatment and caused severe environmental issues. In addition, the entire sago value chain requires high inputs of electrical power and considerable amount of fuel for transportations. This caused significant amount of greenhouse gases, particularly carbon dioxide (CO_2), are emitted from sago value chain to the environment. Hence, water footprint (WFP) and carbon footprint (CFP) are used to assess the environmental performance in the optimal synthesis of a sustainable sago value chain. In addition, due to the involvement of intensive labour in sago value chain, workplace footprint (WPFP), which measures work-related casualties, is taken into consideration. CFP, WFP and WPFP are presented in detail in the following sub-sections.

4.2.1 Carbon Footprint

According to the Wiedmann and Minx (2007), Lam et al. (2010), Galli et al. (2012), and Foo et al. (2013), carbon footprint (CFP) is needed as an index of climate impacts. According to Čuček et al. (2012), there are various definitions for CFP. Conventionally, CFP is defined as total amount of CO_2 and other greenhouse gases (expressed as CO_2 equivalents) emitted over the full life cycle of a process or product (POST, 2006). Meanwhile, land-based CFP is defined as the land area required for the sequestration of fossil-fuel CO_2 emissions from the atmosphere through afforestation (De Benedetto and Klemeš, 2009). In addition, Wiedmann and Minx (2007) defined CFP as a measurement of the exclusive direct (on-site, internal), and indirect (off-side, external, embodies, upstream, and downstream) CO_2 emissions of an activity, or over the life cycle of a product, measured in mass units. In this chapter, the conventional definition of CFP (POST, 2006) is used to measure sustainability of the environment, meaning that the total amount of CO_2 emitted due to land use change (LUC), power and fuel consumption over the full life cycle of sago value chain are considered.

4.2.2 Water Footprint

The water footprint (WFP) methodology introduced by Hoekstra (2003) provides a framework for evaluating and categorising water use in a system and this is essential in synthesising of sustainable sago value chains. According to Gerbens-Leenes et al. (2012), WFP can be used to measure the total amount of direct and indirect water used in the life cycle of a product (Hoekstra, 2003; Hoekstra and Chapagain, 2008; Hoekstra and Chapagain, 2011). In addition, Boulay et al. (2011) reported that WFP could be potentially used as consumption and quality based scarcity indicator to evaluate the effect or impact of reduction in water availability and degradation of water quality to human health. Generally, WFP is divided into three components, which are green, blue, and grey WFP (Gerbens-Leenes et al., 2012). By identifying three categories for water use one is able to identify not only the processes which consume the most amount of water but also the nature by which the system's water use affects the environment. As reported in Gerbens-Leenes et al. (2012), green WFP refers to rainwater that is lost through evapotranspiration during crop cultivation, and is equivalent to the crop water requirement or minimum effective precipitation (FAO, n.d.); in other words, it represents the incremental loss of water in an ecosystem due to the presence of the crop. Blue WFP refers to surface and groundwater which is consumed during production. Finally, grey WFP refers to total freshwater that is required to assimilate the load of discharged pollutants so that the load of pollutants in discharged water will comply with the discharge quality limits. While no actual dilution takes place, grey WFP provides a means of accounting for the presence of pollutants in water. In other words, it accounts for the degradation of the quality of water that is returned in liquid form to the environment. In this chapter, all components of water footprints are used as huge volume of water is required in plantation and sago starch extraction process; and massive volume of wastewater is generated during the extraction process.

4.2.3 Workplace Footprint

Apart from WFP and CFP, workplace footprint (WPFP), which is a work-related casualty indicator, is an important aspect for planning a sustainable sago value chain, which is highly labour-intensive. WPFP was proposed by De Benedetto and Klemeš (2009) as an important dimension in sustainability assessment. Based on the statistic of occupational accidents published in the official website of the Department of Occupational Safety and Health (DOSH) of Malaysia (DOSH, 2013a; DOSH, 2013b), the occupational accidents can be divided into three categories: death, non-permanent disability and permanent disability. Hence, in this chapter, the WPFP is further divided into three categories of risks: Death (D) risk, Permanent Disability (PD) risk and Non-Permanent Disability (NPD) risk.

Since CFP, WFP and WPFP are important indicators in the design of sustainable sago value chain, all these footprints and economic performance are considered simultaneously. Note that the actual valuation of each aspect depends on decision-makers priority; however, an optimisation model allows rational planning to be done once such priorities have been elucidated. Thus, multi-objective optimisation is needed to design an optimum sago value chain while balancing economic performance with these three footprint metrics. In this chapter, a Fuzzy Multi-Footprint optimisation (FMFO) model is developed for this purpose. In this approach, fuzzy set theory is extended to achieve a compromise among the potentially conflicting objectives (Zimmermann, 1978).

4.3 Fuzzy Optimisation Approach

Fuzzy optimisation approach is an approach that able to integrate multiple objectives into single parameter using an overall degree of satisfaction (λ) which is introduced by Zimmermann (1978) and bounded within the interval of 0 to 1 to satisfy all objective functions. In this approach, fuzzy range of each objective is predefined by maximising or minimising the objective functions. This is depended on investor's interest. The highest and lowest value of results of each objective function is defined as upper and lower bound, respectively in fuzzy range. This fuzzy range can be assumed as a linear membership function as showed in Figure 4.2.

For the maximisation case, as shown in Figure 4.2 (a), λ approaches 1 as targeted objective (*obj*) approaches the upper bound and λ approaches 0 as targeted objective (*obj*) approaches the lower bound. To maximise the λ in this case, Equation 4.1 is given as:

$$\frac{Obj - \mathrm{Obj}^{L}}{\mathrm{Obj}^{U} - \mathrm{Obj}^{L}} \geq \lambda \qquad (4.1)$$

where Obj^{U} and Obj^{L} are predefined upper and lower bound in fuzzy range. The *obj* is in between of this range.

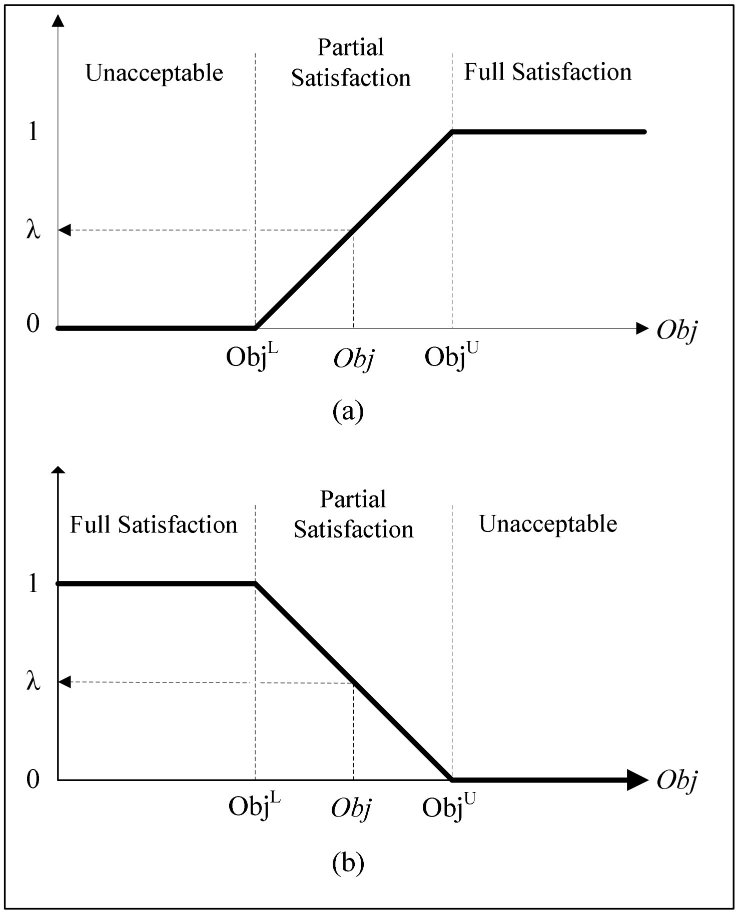

Figure 4.2: Fuzzy degree of satisfaction (λ) of inequalities: (a) maximisation case, (b) minimisation case

In contrast, λ approaches 0 as targeted objective (*obj*) approaches the upper bound and vice versa for the minimisation case as shown in Figure 4.2 (b). The relationship between λ and targeted objectives in this case is given as:

$$\frac{\mathrm{Obj}^{\mathrm{U}} - Obj}{\mathrm{Obj}^{\mathrm{U}} - \mathrm{Obj}^{\mathrm{L}}} \geq \lambda \tag{4.2}$$

The optimum solution is obtained by maximising the least satisfied fuzzy constraint and this is known as "max-min" aggregation (Zimmermann, 1978).

4.4 Problem Statement

The problem definition for Fuzzy Multi-Footprint Optimisation (FMFO) of a sustainable sago value chain is presented as follows: Figure 4.3 shows the generic superstructure of a sago value chain. A set of sago plantation $g \in G$ is given with annual available sago palms, $\mathrm{Z}_{g}^{\mathrm{Palm}}$ that can be harvested to produce a set of bioresource $m \in M$ (sago log, leaflet and rachis). These bioresources m are being sent to sago processing system $f \in F$ to produce a set of products $p \in P$. The annual production capacity of sago processing system f for product p is given as $\mathrm{Z}_{f,p}^{\mathrm{ProSys}}$. The product p is sent to different ports $j \in J$ for exporting to customer $u \in U$ based on product demand, $\mathrm{D}_{u,p}$. The amount of product p transported from sago processing system f to port j is given as $X_{f,p,j}^{\mathrm{ProSys\_Port}}$ while each port capacity is given as $\mathrm{Z}_{j}^{\mathrm{Port}}$. To determine an optimum sustainable sago value chain, FMFO approach is proposed in this work.

4.5 Fuzzy Multi-Footprint Optimisation (FMFO)

As mentioned previously, Fuzzy Multi-Footprint Optimisation (FMFO) is developed in this chapter to trade-off the optimisation objectives. Figure 4.4 shows the proposed methodology to solve FMFO problems. As shown, the superstructure of the value chain is first developed. Then, footprint limits is set for value chain synthesis. The relevant data (e.g., emission factors, water requirements, risks, etc.)

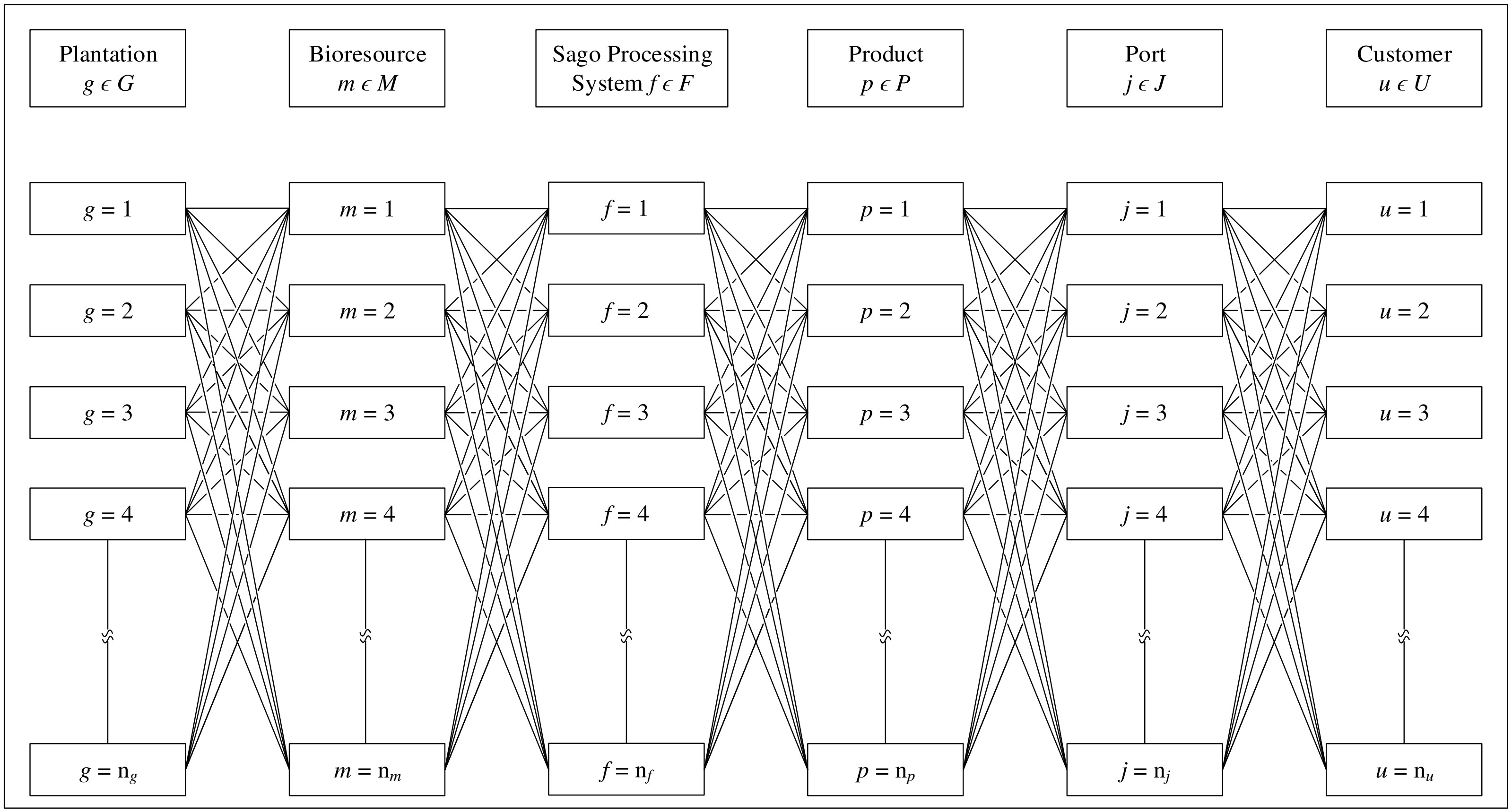

Figure 4.3: Generic superstructure of sago value chain

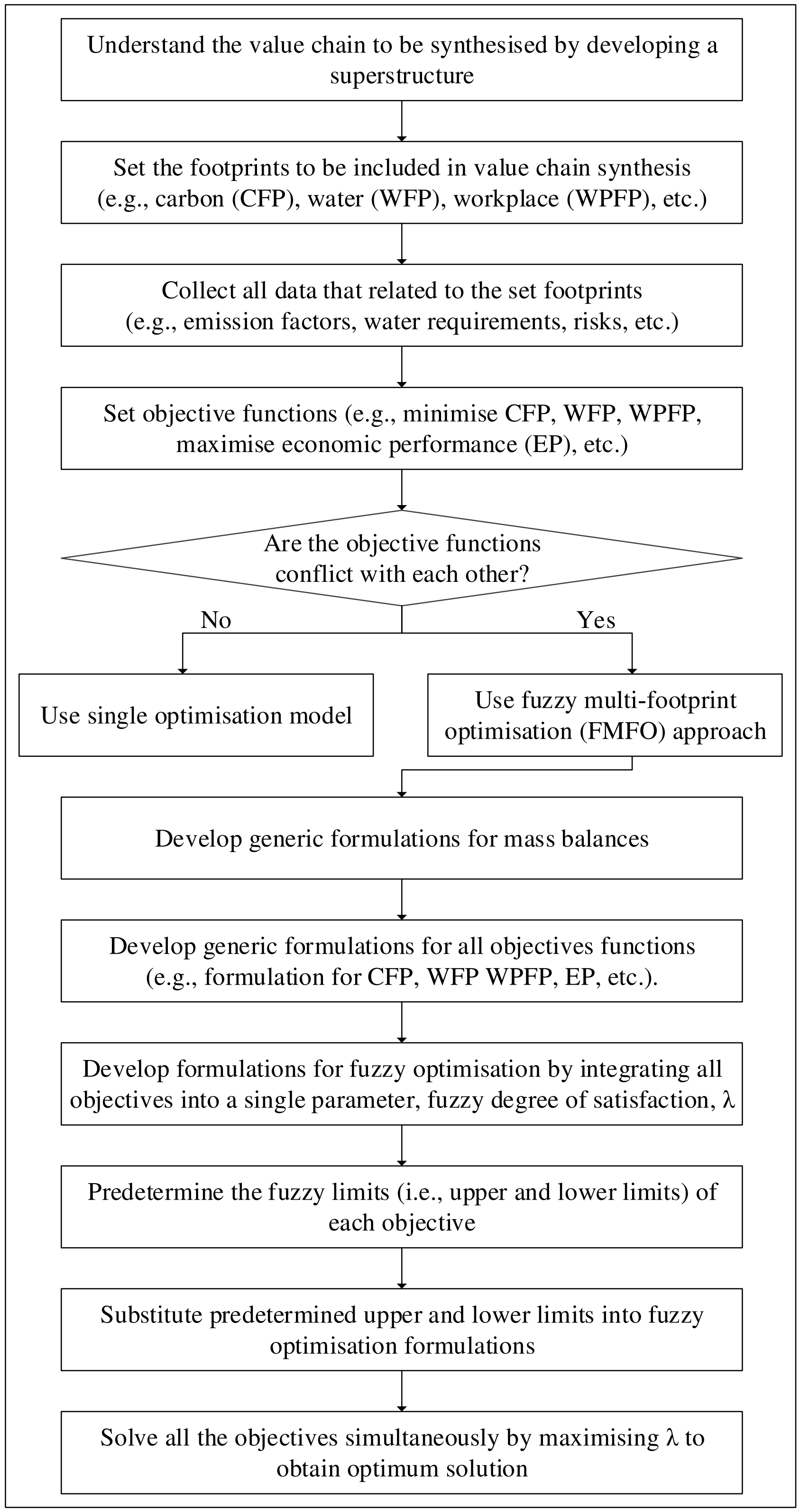

Figure 4.4: The solving procedure of fuzzy multi-footprint optimisation (FMFO) approach

which needed in the selected footprint limits is determined. This is followed by setting the objective functions for value chain synthesis. In this chapter, CFP, WFP, WPFP, and EP are taken into consideration in synthesising a sustainable sago value chain. In most cases, there will be a conflict among the objectives. Therefore, an alternative approach, Fuzzy Multi-Footprint Optimisation (FMFO) model, which adopted the concept of fuzzy optimisation, is used. The subsequent steps of using FMFO approach as shown in Figure 4.3 are presented in the following sub-sections. The formulations of mass balance, CFP, WFP, WPFP, and EP as well as fuzzy optimisation are developed and then solved by the commercial software LINGO v.13. The detailed explanation of the methodology is given in the following sub-sections.

4.6 Formulation

4.6.1 Mass Balances

In plantation g with area, A_g (ha), a total annual available number of sago palm is given as Z_g^{Palm} (palm/y). Palms are harvested to produce bioresource m for the production of product p which is needed by customer u. The total number of palms that are harvested annually from plantation g is represented as H_g (palm/y). To ensure a sustainable harvesting process, H_g should be lower than the available amount of sago palm (Z_g^{Palm}), as:

$$Z_g^{\text{Palm}} \geq H_g \qquad \forall g \qquad (4.3)$$

Given the conversion rate of palm to bioresource m in plantation g as $V_{g,m}$, and the total amount of bioresource m, $X_{g,m}^{\text{Plant}}$ can be determined via:

$$X_{g,m}^{\text{Plant}} = H_g V_{g,m} \qquad \forall g \forall m \qquad (4.4)$$

Since H_g is the number of palms that are harvested, it is always a positive integer (I = 0, 1, 2,…, n), as shown in Equation (4.5).

$$H_g \in \text{I} \qquad \forall g \forall m \qquad (4.5)$$

In current industrial practice, only one of the bioresources m, sago log (Log) is sent to sago processing system for further processing to produce product p. Hence, Equations (4.4) is reformulated as:

$$X_{g,\text{Log}}^{\text{Plant}} = H_g V_{g,\text{Log}} \qquad \forall g \qquad (4.6)$$

where $X_{g,\text{Log}}^{\text{Plant}}$ is the annual production of sago log (log/y) and $V_{g,\text{Log}}$ is the conversion rate of palm to log (log/palm) from plantation g. The harvested sago logs from plantation g are then transported to sago processing system f ($X_{g,f}^{\text{Plant\_ProSys}}$) for further processing.

$$X_{g,\text{Log}}^{\text{Plant}} = \sum_f X_{g,f}^{\text{Plant\_ProSys}} \qquad \forall g \qquad (4.7)$$

Note that the sago logs can be sent to the sago processing system via either river or road transportation. However, only road transportation is considered in this chapter, as the impacts of river transportation are low and can be neglected. In order to determine the required number of trips to transport the sago logs from plantation g to the sago processing system f $\left(n_{g,f}^{\mathrm{Trip}}\right)$ via road transportation, total weight of logs that transported from plantation g to sago processing system f ($W_{g,f}^{\mathrm{Plant\_ProSys}}$) is first determined as shown in Equation (4.8). Then, number of trips from plantation g to sago processing system f ($n_{g,f}^{\mathrm{Trip}}$) can be determined via Equation (4.9).

$$W_{g,f}^{\mathrm{Plant\_ProSys}} = X_{g,f}^{\mathrm{Plant\_ProSys}} \mathrm{q}_{g,\mathrm{Log}} \qquad \forall g \forall f \qquad (4.8)$$

$$n_{g,f}^{\mathrm{Trip}} \geq \frac{W_{g,f}^{\mathrm{Plant\_ProSys}}}{\mathrm{Z}^{\mathrm{Lorry}}} \qquad \forall g \forall f \qquad (4.9)$$

$$n_{g,f}^{\mathrm{Trip}} \in \mathrm{I} \qquad \forall g \forall f \qquad (4.10)$$

where $\mathrm{Z}^{\mathrm{Lorry}}$ (t/trip) is the lorry capacity, and $\mathrm{q}_{g,\mathrm{Log}}$ (t/log) is the average weight of the sago log. Meanwhile, $n_{g,f}^{\mathrm{Trip}}$ is a positive integer (I = 0, 1, 2……, n).

In sago processing system f, sago logs are converted into product p (e.g., starch, barks and fibres) based on the conversion rate of $\mathrm{V}_{f,p}$. The production of product p in sago processing system f, $X_{f,p}^{\mathrm{ProSys}}$ (t/y) can be determined via:

$$X_{f,p}^{\mathrm{ProSys}} = \sum_{g} W_{g,f}^{\mathrm{Plant\_ProSys}} \mathrm{V}_{f,p} \qquad \forall f \forall p \qquad (4.11)$$

Since there are limited number of existing sago processing system, $X_{f,p}^{\text{ProSys}}$ is subjected to the maximum production capacity of the sago processing system, $\text{Z}_{f,p}^{\text{ProSys}}$. Thus, Equation (4.12) is included in the model.

$$X_{f,p}^{\text{ProSys}} \leq \text{Z}_{f,p}^{\text{ProSys}} \qquad \forall f \forall p \qquad (4.12)$$

In addition, since product *p* is produced based on the conversion of sago logs that comes from plantation *g*, the annual yield of product *p* based on plantation area, $\text{S}_{g,p}$ (t/ha-y) can be determined via:

$$\text{S}_{g,p} = \text{K}_{g}^{\text{Plant}} \text{V}_{g,\text{Log}} \text{L}_{g,p} \qquad \forall g \forall p \qquad (4.13)$$

where $\text{K}_{g}^{\text{Plant}}$ represents the total number of palms in one hectare of plantation *g* annually (palm/ha-y) and $\text{V}_{g,\text{Log}}$ is the conversion rate of palm to log (log/palm) from plantation *g*. Meanwhile, $\text{L}_{g,p}$ is the extractable product *p* from sago log (t/log) that is harvested from plantation *g*. Note that $\text{L}_{g,p}$ of each plantation is different as this depends on soil condition.

A considerable volume of water is required the conversion of sago logs into product *p* in sago processing system *f*. Furthermore, wastewater is generated. In this chapter, the water required for a ton of product *p* produced is known as product water requirement (PWR) (m^3/t), which is equivalent to the total amount of water that is consumed or evaporated during processing. In order to determine the volume of wastewater per ton of product p produced in sago processing system f, $\mathrm{F}_{f,p}^{\mathrm{Out}}$ (m^3/t), the following equation is given:

$$\mathrm{F}_{f,p}^{\mathrm{Out}} = \mathrm{F}_{f,p}^{\mathrm{In}} - \mathrm{PWR}_{f,p} \qquad \forall f \forall p \qquad (4.14)$$

where $\mathrm{F}_{f,p}^{\mathrm{In}}$ is the total volume of inlet water of sago processing system f to produce one ton of product p (m^3/t). Meanwhile, $\mathrm{PWR}_{f,p}$ is the PWR of sago processing system f to produce products p (m^3/t). Hence, the total wastewater that is generated in sago processing system f for product p , $TotWW_{f,p}$ (m^3/y), is given as:

$$TotWW_{f,p} = X_{f,p}^{\mathrm{ProSys}} \mathrm{F}_{f,p}^{\mathrm{Out}} \qquad \forall f \forall p \qquad (4.15)$$

Once product p is ready, it is then packed and distributed to different ports j. The distribution of product p is given as:

$$X_{f,p}^{\mathrm{ProSys}} = \sum_{j} X_{f,p,j}^{\mathrm{ProSys\_Port}} \qquad \forall f \forall p \qquad (4.16)$$

where $X_{f,p,j}^{\mathrm{ProSys\_Port}}$ is the total amount of product p that is sent from sago processing system f to port j. Meanwhile, the number of trips from the sago processing system to the ports ($n_{f,p,j}^{\mathrm{Trip}}$) can be determined by dividing $X_{f,p,j}^{\mathrm{ProSys\_Port}}$ with $\mathrm{Z}^{\mathrm{Lorry}}$ as shown below:

$$n_{f,p,j}^{\text{Trip}} \geq \frac{X_{f,p,j}^{\text{ProSys\_Port}}}{Z^{\text{Lorry}}} \; ; \qquad \forall f \forall p \forall j \qquad (4.17)$$

Similar with Equation (4.10), $n_{f,p,j}^{\text{Trip}}$ is always a positive integer.

$$n_{f,p,j}^{\text{Trip}} \in \text{I} \qquad \forall f \forall j \qquad (4.18)$$

On the other hand, the total product *p* that is received by port *j* is given as:

$$X_{p,j}^{\text{Port}} = \sum_{f} X_{f,p,j}^{\text{ProSys\_Port}} \qquad \forall p \forall j \qquad (4.19)$$

To determine total product *p* that is sent to port *j*, the equation below is included in the model:

$$X_{j}^{\text{Port}} = \sum_{p} X_{p,j}^{\text{Port}} \qquad \forall j \qquad (4.20)$$

Due to the limitation of storage capacity at port *j* (Z_j^{Port}), X_j^{Port} must be less than the storage capacity of each port, as given below:

$$X_{j}^{\text{Port}} \leq Z_{j}^{\text{Port}} \qquad \forall j \qquad (4.21)$$

The product *p* is then delivered to customer *u* through port *j* as shown below:

$$X_{p,j}^{\text{Port}} = \sum_{u} X_{p,j,u}^{\text{Port\_Cust}} \qquad \forall p \, \forall j \qquad (4.22)$$

where $X_{p,j,u}^{\text{Port\_Cust}}$ is the amount of product p that is shipped from port j to customer u via sea transportation. The number of containers that is required to be shipped from ports j to customer u, $n_{p,j,u}^{\text{Ctn}}$ can be determined via:

$$n_{p,j,u}^{\text{Ctn}} \geq \frac{X_{p,j,u}^{\text{Port\_Cust}}}{\text{Z}^{\text{TEU}}} \qquad \forall p \, \forall j \, \forall u \qquad (4.23)$$

$$n_{p,j,u}^{\text{Ctn}} \in \text{I} \qquad \forall p \, \forall j \, \forall u \qquad (4.24)$$

where Z^{TEU} is the given capacity of a standard shipping container and $n_{p,j,u}^{\text{Ctn}}$ is a positive integer. Note that product p is supplied to customer u based on the demand range of the customer, as given:

$$\text{D}_{p,u}^{\text{LL}} \leq \sum_{j} X_{p,j,u}^{\text{Port\_Cust}} \leq \text{D}_{p,u}^{\text{UL}} \qquad \forall p \, \forall u \qquad (4.25)$$

where $\text{D}_{p,u}^{\text{UL}}$ and $\text{D}_{p,u}^{\text{LL}}$ are the upper and lower demand limits for product p of customer u.

4.6.2 Water Footprint (WFP) Computation

In this chapter, all the water consumed and generated in activities of sago value chain is considered. Therefore, green WFP, blue WFP, grey WFP, power-based and fuel-based WFP are taken into consideration. The green WFP of sago value chain can be determined by determining the crop water requirement (CWR) in each plantation as noted in Section 4.2.2. Note that a sago plantation requires a minimum rainfall (RAIN) of 2000 millimetre per year (Flach, 1997). Based on RAIN, CWR (m^3/t) can be determined via Equation (4.26):

$$\mathrm{CWR}_{g,p} = \frac{\mathrm{RAIN}}{\mathrm{S}_{g,p}} \qquad \forall g \, \forall p \qquad (4.26)$$

Thus, total green WFP, $TotWFP^{\mathrm{Green}}$ (m^3/y), is determined via:

$$TotWFP^{\mathrm{Green}} = \sum_{f} \sum_{p} \sum_{g} \mathrm{CWR}_{g,p} X_{f,p}^{\mathrm{ProSys}} \qquad (4.27)$$

Total blue WFP, $TotWFP^{\mathrm{Blue}}$ (m^3/y) can be determined via:

$$TotWFP^{\mathrm{Blue}} = \sum_{f} \sum_{p} \mathrm{PWR}_{f,p} X_{f,p}^{\mathrm{ProSys}} \qquad (4.28)$$

Next, grey WFP can be determined based on the load of pollutant *b* in the discharged water, $\mathrm{M}_{f,p,b}^{\mathrm{Out}}$ (g/t), the required freshwater (FWR) (m^3/t) and the water discharge limit. Note that pollutant b is usually measured in concentration basis, thus, $\mathrm{CC}_{f,p,b}^{\mathrm{Out}}$ (g/m^3) is given to represent the concentration of pollutant b in wastewater. To determine $\mathrm{M}_{f,p,b}^{\mathrm{Out}}$, Equation (4.29) is formulated.

$$\mathrm{M}_{f,p,b}^{\mathrm{Out}} = \mathrm{CC}_{f,p,b}^{\mathrm{Out}} \mathrm{F}_{f,p}^{\mathrm{Out}} \qquad \forall f \forall p \forall b \qquad (4.29)$$

In addition, FWR is referred to as the amount of freshwater that is required to assimilate the load of the pollutant in the discharged water so that the water complies with the discharge limit (Gerbens-Leenes et al., 2012) for a ton of product p. However, it is important to note that the wastewater is not actually diluted with freshwater in order to comply with the discharge limit but that the grey WFP serves only as an indicator of the intensity by which the wastewater impacts the environment. To determine FWR, the equation below is included in the model.

$$\mathrm{FWR}_{f,p} \geq \frac{\mathrm{M}_{f,p,b}^{\mathrm{Out}}}{\mathrm{CC}_{b}^{\mathrm{Dis}}} \qquad \forall f \forall p \forall b \qquad (4.30)$$

where $\mathrm{CC}_{b}^{\mathrm{Dis}}$ is the discharge concentration limit of pollutant b. Then, total grey WFP, $TotWFP^{\mathrm{Grey}}$ (m^3/y) can be determined via:

$$TotWFP^{\mathrm{Grey}} = \sum_{f} \sum_{p} \mathrm{FWR}_{f,p} X_{f,p}^{\mathrm{ProSys}} \qquad (4.31)$$

where $\mathrm{FWR}_{f,p}$ is FWR of sago processing system f to produce product p.

Apart from green, blue and grey WFP, power-based WFP and fuel-based WFP are also considered in this chapter. Power and fuel-based WFP refers to the total water that is consumed for power and fuel generation. In order to determine power-based WFP ($TotWFP^{\text{Power}}$), equation below is given:

$$TotWFP^{\text{Power}} = \sum_{f}\sum_{p} \text{WR}^{\text{Power}} \text{E}_{f,p} X_{f,p}^{\text{ProSys}} \tag{4.32}$$

where WR^{Power} (m^3/kWh) is water requirement for power generation. Fuel-based WFP can be divided into road transportation and sea transportation. The following equations below are formulated to determine the total WFP of road transportation from the plantations to the processing system ($TotWFP^{\text{Road\_Plant\_ProSys}}$) ($m^3$/y) and from the sago processing system to the ports ($TotWFP^{\text{Road\_ProSys\_Port}}$) ($m^3$/y).

$$TotWFP^{\text{Road\_Plant\_ProSys}} = \sum_{g}\sum_{f} \text{WR}^{\text{Road}} \text{Z}^{\text{Lorry}} \text{d}_{g,f} n_{g,f}^{\text{Trip}} \tag{4.33}$$

$$TotWFP^{\text{Road\_ProSys\_Port}} = \sum_{f}\sum_{p}\sum_{j} \text{WR}^{\text{Road}} \text{Z}^{\text{Lorry}} \text{d}_{f,j} n_{f,p,j}^{\text{Trip}} \tag{4.34}$$

where WR^{Road} (m^3/kg.km) is the volume of water required to deliver the product. This parameter is determined based on total average water footprint for crude oil production (1.058 m^3/GJ) (Gerbens-Leenes et al., 2008) and the estimated average energy required for a lorry (2.3 MJ/km-t) to deliver 1 ton of material (Gerbens-Leenes and Hoekstra, 2011). Meanwhile, the total WFP of sea transportation from ports to customers ($TotWFP^{\text{Sea\_Port\_Cust}}$) ($m^3$/y) is determined via Equation (4.35):

$$TotWFP^{\text{Sea\_Port\_Cust}} = \sum_{p}\sum_{j}\sum_{u} \text{WR}^{\text{Sea}} \text{Z}^{\text{TEU}} \text{d}_{j,u} n^{\text{Ctn}}_{p,j,u} \tag{4.35}$$

where WR^{Sea} (m^3/t-km) is the required volume of water to deliver products to customers via sea transportation. Similarly, WR^{Sea} is determined based on total average water footprint for crude oil production (1.058 m^3/GJ) and the energy required for a ship (0.095 MJ/km-t) to deliver 1 ton of material. By summing up the WFPs, the total WFP of sago value chain, on a yearly basis, *TotWFP* (m^3/y) can be determined as shown below:

$$TotWFP = TotWFP^{\text{Green}} + TotWFP^{\text{Blue}} + TotWFP^{\text{Grey}} + TotWFP^{\text{Power}} + TotWFP^{\text{Road\_Plant\_ProSys}} + TotWFP^{\text{Road\_ProSys\_Port}} + TotWFP^{\text{Sea\_Port\_Cust}} \tag{4.36}$$

4.6.3 Carbon Footprint (CFP) Computation

In order to determine CFP of the sago value chain, an average annual level of carbon debt of a plantation, DEBT^{C}, is first determined by allocating the initial emission from land use change (LUC) (70 kg/m^2) (Fargione et al., 2007) over a 30 year time horizon (DEBT^{C} = 70/30 = 2.33 kg/m^2.y) (Tan et al., 2009). Then, the total carbon footprint of each plantation *g* converted from LUC, $\text{TotCFP}^{\text{LUC}}_{g}$, can be determined via:

$$\text{TotCFP}^{\text{LUC}}_{g} = \text{DEBT}^{\text{C}} \text{A}_{g} (10000) \qquad \forall g \tag{4.37}$$

where the conversion factor of 10,000 m^2/ha is used to convert hectare (ha) to m^2. All of the plantation's carbon footprint due to LUC are then summed up to determine total LUC carbon footprint, $\mathrm{TotCFP}^{\mathrm{LUC}}$, as given:

$$\mathrm{TotCFP}^{\mathrm{LUC}} = \sum_{g} \mathrm{TotCFP}_{g}^{\mathrm{LUC}} \tag{4.38}$$

Next, the total amount of power and fuel consumed in the sago value chain is determined. Based on the power and fuel required, the total power-based CFP ($TotCFP^{\mathrm{Power}}$) and total fuel-based CFP ($TotCFP^{\mathrm{Fuel\_Plant\_ProSys}}$, $TotCFP^{\mathrm{Fuel\_ProSys\_Port}}$, $TotCFP^{\mathrm{Fuel\_Port\_Cust}}$) can be determined via the following equations.

$$TotCFP^{\mathrm{Power}} = \sum_{f} \sum_{p} \mathrm{EF}^{\mathrm{Power}} \mathrm{E}_{f,p} X_{f,p}^{\mathrm{ProSys}} \tag{4.39}$$

where $\mathrm{EF}^{\mathrm{Power}}$ is the emission factor of power generation ($kgCO_2$/kWh) and $\mathrm{E}_{f,p}$ is the power consumed in sago processing system f to convert sago logs into product p (kWh/kg). Note that $\mathrm{EF}^{\mathrm{Power}}$ can be determined based on the power (PW_{pp}) generated by the individual power plant and the emission factor (EF_{pp}) of each power plant, as shown in Table A7 (see Appendix A). Meanwhile, the total fuel-based CFP can be determined via:

$$TotCFP^{\mathrm{Fuel\_Plant\_ProSys}} = \sum_{g} \sum_{f} \mathrm{EF}^{\mathrm{Fuel\_Road}} \mathrm{Z}^{\mathrm{Lorry}} \mathrm{d}_{g,f} n_{g,f}^{\mathrm{Trip}} \tag{4.40}$$

$$TotCFP^{\text{Fuel\_ProSys\_Port}} = \sum_{f}\sum_{p}\sum_{j} \text{EF}^{\text{Fuel\_Road}} \text{Z}^{\text{Lorry}} \text{d}_{f,j} n^{\text{Trip}}_{f,p,j} \tag{4.41}$$

$$TotCFP^{\text{Fuel\_Port\_Cust}} = \sum_{p}\sum_{j}\sum_{u} \text{EF}^{\text{Fuel\_Sea}} \text{Z}^{\text{TEU}} \text{d}_{j,u} n^{\text{Ctn}}_{p,j,u} \tag{4.42}$$

where $TotCFP^{\text{Fuel\_Plant\_ProSys}}$, $TotCFP^{\text{Fuel\_ProSys\_Port}}$, $TotCFP^{\text{Fuel\_Port\_Cust}}$ are the total amounts of CO_2 emitted from plantations to sago processing system (kgCO_2/y), from processing system to ports (kgCO_2/y) and from ports to customers (kgCO_2/y), respectively. Meanwhile, $\text{EF}^{\text{Fuel\_Road}}$ is the emission factor of road transportation (kgCO_2/km-t) and $\text{EF}^{\text{Fuel\_Sea}}$ is the emission factor of sea transportation (kgCO_2/km/-t). Based on Equations (4.37) – (4.42), the total CFP of the sago value chain can be determined by summing up all CFP as shown below:

$$TotCFP = \text{TotCFP}^{\text{LUC}} + TotCFP^{\text{Power}} + TotCFP^{\text{Fuel\_Plant\_ProSys}} + TotCFP^{\text{Fuel\_ProSys\_Port}} + TotCFP^{\text{Fuel\_Port\_Cust}} \tag{4.43}$$

4.6.4 Workplace Footprint (WPFP) Computation

As mentioned previously, in this chapter, WPFP is divided into death risk, NPD risk and PD risk. To simplify the model, these risks are only considered in the high risk activities (i.e., harvesting, processing, port handling, transportation), which involved intensive labour and heavy machinery. Besides, risks of transportations are considered in this chapter to determine an optimum pathway with minimum risks. Equations (4.44) – (4.50) are shown to determine total death risk in a yearly basis (deaths/y). Total NPD and PD risks can also be determined via the same set of equations by replacing the death risks with the respective risk of interest. Total harvesting death risk ($TotR^{\text{Harv\_D}}$), total processing death risk ($TotR^{\text{Process\_D}}$), total handling death risk ($TotR^{\text{Port\_D}}$), and total road transportation death risks ($\text{TotR}^{\text{Plant\_ProSys\_D}}$ and $\text{TotR}^{\text{ProSys\_Port\_D}}$) as well as total sea transportation death risk ($TotR^{\text{Sea\_D}}$) can be determined via the following equations.

$$TotR^{\text{Harv\_D}} = \sum_g H_g \text{r}_g^{\text{Harv\_D}} \tag{4.44}$$

$$TotR^{\text{Process\_D}} = \sum_f \left(\sum_p X_{f,p}^{\text{ProSys}} \right) \text{r}_f^{\text{Process\_D}} \tag{4.45}$$

$$TotR^{\text{Port\_D}} = \sum_j X_j^{\text{Port}} \text{r}_j^{\text{Port\_D}} \tag{4.46}$$

$$TotR^{\text{Plant\_ProSys}} = \sum_y \left(\sum_f \sum_g n_{g,f}^{\text{Trip}} \text{d}_{g,y,f} \right) \text{r}_y^{\text{Road\_D}} \tag{4.47}$$

$$TotR^{\text{ProSys\_Port}} = \sum_y \left(\sum_p \sum_j \sum_f \text{d}_{f,y,j} n_{f,p,j}^{\text{Trip}} \right) \text{r}_y^{\text{Road\_D}} \tag{4.48}$$

$$TotR^{\text{Sea\_D}} = \left(\sum_u \sum_p \sum_j \frac{\text{d}_{j,u} n_{p,j,u}^{\text{Ctn}}}{\text{n}^{\text{CPT}}} \right) \text{r}^{\text{Sea\_D}} \tag{4.49}$$

where $\text{r}_g^{\text{Harv\_D}}$, $\text{r}_f^{\text{Process\_D}}$, $\text{r}_j^{\text{Port\_D}}$, $\text{r}_y^{\text{Road\_D}}$ and $\text{r}^{\text{Sea\_D}}$ are the death risks from harvesting (deaths/palm), processing (deaths/t), port handling (deaths /t), road transportation (deaths /km) and sea transportation (deaths /km), respectively. Note that the level of risk of each district is different. Therefore, index y is introduced to represent the districts that passed from plantation g to sago processing system f or from sago processing system f to port j. In order to determine total death risk of the sago value chain, $TotR^{D}$ (deaths /y) in a yearly basis, all risks are summed up as below:

$$TotaR^{D} = TotR^{Harv\_D} + TotR^{Process\_D} + TotR^{Port\_D} + TotR^{Plant\_ProSys\_D} + TotR^{ProSys\_Port\_D} + TotR^{Sea\_D} \quad (4.50)$$

In order to show the significance of these risks, a comparison table is given in the case study section.

4.6.5 Economic Performance Evaluation

The economic potential of plantations, sago processing system and ports can be used to evaluate the profitability of the sago value chain. In this chapter, economic potential is defined as the difference between total revenue and total cost. In order to determine total costs of plantation g ($TotCost^{Plant}$), the total harvesting cost ($TotCost^{Harv}$) and total transportation cost from plantations to sago processing system ($TotCost^{Plant\_ProSys}$) are considered and summed up as shown in the following equations:

$$TotCost^{Harv} = \sum_{g} \mathrm{UCost}_{g}^{Harv} H_{g} \quad (4.51)$$

$$TotCost^{Plant\_ProSys} = \sum_{g} \sum_{f} \mathrm{UCost}^{Road} \mathrm{d}_{g,f} n_{g,f}^{Trip} \quad (4.52)$$

$$TotCost^{Plant} = TotCost^{Harv} + TotCost^{Plant\_ProSys} \quad (4.53)$$

where $\mathrm{UCost}_{g}^{\mathrm{Harv}}$ and $\mathrm{UCost}^{\mathrm{Road}}$ are the unit cost of harvesting (MYR/palm) and road transportation (MYR/km), respectively. Note that in this chapter, it is given that 1 MYR is equal to 0.30 USD. Meanwhile, $\mathrm{d}_{g,f}$ is the actual travel distances between plantation g and sago processing system f (km), based on google map. Since most of the sago palms grows in wild and can be self-reproduced after every harvesting process (Singhal et al., 2008), no additional cost for investment is taken into consideration in this chapter for sago plantation.

In sago processing system f, total raw material cost ($TotCost^{\mathrm{RawMat}}$), total processing cost ($TotCost^{\mathrm{Process}}$), and total transportation cost from sago processing system to ports ($TotCost^{\mathrm{ProSys\_Port}}$) are taken into consideration to determine the total cost of the sago processing system ($TotCost^{\mathrm{ProSys}}$). These costs can be determined via the following equations:

$$TotCost^{\mathrm{RawMat}} = \sum_{g}\sum_{f} X_{g,f}^{\mathrm{Plant\_ProSys}}\,\mathrm{UCost}_{g,f}^{\mathrm{Log}} \tag{4.54}$$

$$TotCost^{\mathrm{Process}} = \sum_{f}\sum_{p} X_{f,p}^{\mathrm{ProSys}}\,\mathrm{UCost}_{f,p}^{\mathrm{Process}} \tag{4.55}$$

$$TotCost^{\mathrm{ProSys\_Port}} = \sum_{f}\sum_{j} \mathrm{UCost}^{\mathrm{Road}}\,\mathrm{d}_{f,j}\,n_{f,j}^{\mathrm{Trip}} \tag{4.56}$$

$$TotCost^{\mathrm{ProSys}} = TotCost^{\mathrm{RawMat}} + TotCost^{\mathrm{Process}} + TotCost^{\mathrm{ProSys\_Port}} \tag{4.57}$$

where $\mathrm{UCost}_{g,f}^{\mathrm{Log}}$ is the unit cost of sago log (MYR/log), $\mathrm{UCost}_{f,p}^{\mathrm{Process}}$ is the unit cost of processing in sago processing system f into product p (MYR/t) and $\mathrm{d}_{f,j}$ is the actual travel distances between sago processing system f and ports j (km).

In port j, the total purchasing cost of products p from sago processing system f ($TotCost^{\text{Prod}}$) and total handling cost ($TotCost^{\text{Handling}}$) are given as Equations (4.58) and (4.59), respectively. Apart from these, the sea freight cost from port to customer ($TotCost^{\text{Port\_Cust}}$) can be determined via Equation (4.60). These costs are then summed up to determine total cost of port ($TotCost^{\text{Port}}$) as given in Equation (4.61).

$$TotCost^{\text{Prod}} = \sum_{p}\sum_{j} X_{p,j}^{\text{Port}} \text{UCost}_{p,j}^{\text{Port}} \tag{4.58}$$

$$TotCost^{\text{Handling}} = \sum_{p}\sum_{j}\sum_{u} n_{p,j,u}^{\text{Ctn}} \text{UCost}_{j}^{\text{Handling}} \tag{4.59}$$

$$TotCost^{\text{Port\_Cust}} = \sum_{p}\sum_{j}\sum_{u} \frac{n_{p,j,u}^{\text{Ctn}}}{\text{n}^{\text{CPT}}} \text{UCost}_{j,u}^{\text{Port\_Cust}} \tag{4.60}$$

$$TotCost^{\text{Port}} = TotCost^{\text{Prod}} + TotCost^{\text{Handling}} + TotCost^{\text{Port\_Cust}} \tag{4.61}$$

where $\text{UCost}_{p,j}^{Port}$, $\text{UCost}_{j}^{\text{Handling}}$ and $\text{UCost}_{j,u}^{\text{Port\_Cust}}$ are the purchasing unit cost (MYR/kg), handling unit cost (MYR/container) and sea freight cost (MYR/trip), respectively. Meanwhile, n^{CPT} is the number of containers that must be shipped in a single trip.

In order to determine the total revenue of the plantation ($TotRV^{\text{Plant}}$), sago processing system ($TotRV^{\text{ProSys}}$) and ports ($TotRV^{\text{Port}}$) the following equations are included in the optimisation model.

$$TotRV^{\text{Plant}} = \sum_{g}\sum_{f} \text{SP}_{g,f}^{\text{Log}} X_{g,f}^{\text{Plant\_ProS ys}} \tag{4.62}$$

$$TotRV^{\text{ProSys}} = \sum_{f}\sum_{p}\sum_{j} \text{SP}_{f,p,j}^{\text{ProSys\_Port}} X_{f,p,j}^{\text{ProSys\_Port}} \tag{4.63}$$

$$TotRV^{\text{Port}} = \sum_{p}\sum_{j}\sum_{u} \text{SP}_{p,j,u}^{\text{Port\_Cust}} X_{p,j,u}^{\text{Port\_Cust}} \tag{4.64}$$

where $\text{SP}_{g,f}^{\text{Log}}$ are the selling price of sago logs from plantation g to sago processing system f (MYR/log); $\text{SP}_{f,p,j}^{\text{ProSys\_Port}}$ and $\text{SP}_{p,j,u}^{\text{Port\_Cust}}$ are the selling price of product p from sago processing system to port j (MYR/kg) and port j to customer u (MYR/kg), respectively. Based on the total revenue and costs, the economic potential of plantations ($TotEP^{\text{Plant}}$), sago processing system ($TotEP^{\text{ProSys}}$) and ports ($TotEP^{\text{Port}}$) can be determined via the following equations:

$$TotEP^{\text{Plant}} = TotRV^{\text{Plant}} - TotCost^{\text{Plant}} \tag{4.65}$$

$$TotEP^{\text{ProSys}} = TotRV^{\text{ProSys}} - TotCost^{\text{ProSys}} \tag{4.66}$$

$$TotEP^{\text{Port}} = TotRV^{\text{Port}} - TotCost^{\text{Port}} \tag{4.67}$$

Based on the above economic evaluation, economic potential of the sago value chain, $TotEP$ can be determined via:

$$TotEP = TotEP^{\text{Plant}} + TotEP^{\text{ProSys}} + TotEP^{\text{Port}} \tag{4.68}$$

4.6.6 Fuzzy Optimisation

In order to address multiple objective functions that are often contradictory, fuzzy optimisation is adapted to solve the optimisation problem in this chapter. Note that fuzzy optimisation approach is adopted in this chapter, as it can avoid any bias weighting factor that need to be predefined in weighting sum approach. Note also that alternative multiple-objective optimisation approaches (e.g., bi-level optimisation, etc.) can also be included in the analysis. Based on the concept of “max-min” aggregation in fuzzy optimisation (Zimmermann, 1978), the optimum solution can be obtained by maximising the least satisfied constraint (Aviso et al., 2010b). Fuzzy optimisation integrates multiple objectives into a single variable, the fuzzy degree of satisfaction, λ, which ranges in value from 0 to 1. In this chapter, all the objective functions are integrated into λ as shown in the following equations.

$$\frac{TotEP - EP^{\mathrm{LL}}}{EP^{\mathrm{UL}} - EP^{\mathrm{LL}}} \geq \lambda \tag{4.69}$$

$$\frac{R^{\mathrm{D\_UL}} - TotR^{\mathrm{D}}}{R^{\mathrm{D\_UL}} - R^{\mathrm{D\_LL}}} \geq \lambda \tag{4.70}$$

$$\frac{R^{\mathrm{PD\_UL}} - TotR^{\mathrm{PD}}}{R^{\mathrm{PD\_UL}} - R^{\mathrm{PD\_LL}}} \geq \lambda \tag{4.71}$$

$$\frac{R^{\mathrm{NPD\_UL}} - TotR^{\mathrm{NPD}}}{R^{\mathrm{NPD\_UL}} - R^{\mathrm{NPD\_LL}}} \geq \lambda \tag{4.72}$$

$$\frac{CFP^{\mathrm{UL}} - TotCFP}{CFP^{\mathrm{UL}} - CFP^{\mathrm{LL}}} \geq \lambda \tag{4.73}$$

$$\frac{WFP^{\mathrm{UL}} - TotWFP}{WFP^{\mathrm{UL}} - WFP^{\mathrm{LL}}} \geq \lambda \tag{4.74}$$

where EP^{UL}, $R^{\mathrm{D\_UL}}$, $R^{\mathrm{NPD\_UL}}$, $R^{\mathrm{PD\_UL}}$, CFP^{UL} and WFP^{UL} are the predetermined upper limits of economic potential, death risk, NPD risk, PD risk, CFP and WFP of the sago value chain, respectively. Meanwhile, EP^{LL}, $R^{\mathrm{D\_LL}}$, $R^{\mathrm{NPD\_LL}}$, $R^{\mathrm{PD\_LL}}$, CFP^{LL}

and WFP^{LL} are the predetermined lower limits of economic potential, death risk, NPD risk, PD risk, CFP and WFP of sago value chain, respectively. In this chapter, these limits are determined based on the maximum and minimum values that determined by optimising the model one objective at a time. Next, the predetermined fuzzy limits are substituted into Equations (4.69) – (4.74) so that all the objectives can be solved simultaneously by maximising the fuzzy degree of satisfaction, λ, as given:

$$\text{Maximise } \lambda \tag{4.75}$$

4.7 Case Study

To illustrate the proposed approach, a sago value chain case study from Sarawak in eastern Malaysia is solved. Figure 4.5 shows the superstructure that illustrates all the possible pathways in the sago value chain. As shown in Figure 4.5, sago logs (bioresource) are produced from different plantations and sent to different sago mills, which is a sago processing systems, to produce sago starch (product). Sago starch is then delivered to customers via different ports.

Data for this value chain, such as total availability of sago palm, extractable starch of sago log, capacities of sago mills and ports, as well as demand range of the customers are all given in Table A1 (Appendix A of this thesis). According to the sago mill owner, the conversion rate of palm to logs ($V_{g,\mathrm{Log}}$), and the weight of sago log ($q_{g,\mathrm{Log}}$), are given as 10 logs/palm and 0.05 t/log, respectively. Since sago starch is the only product in this case, the extractable starch in sago log ($L_{g,p}$) and the yield

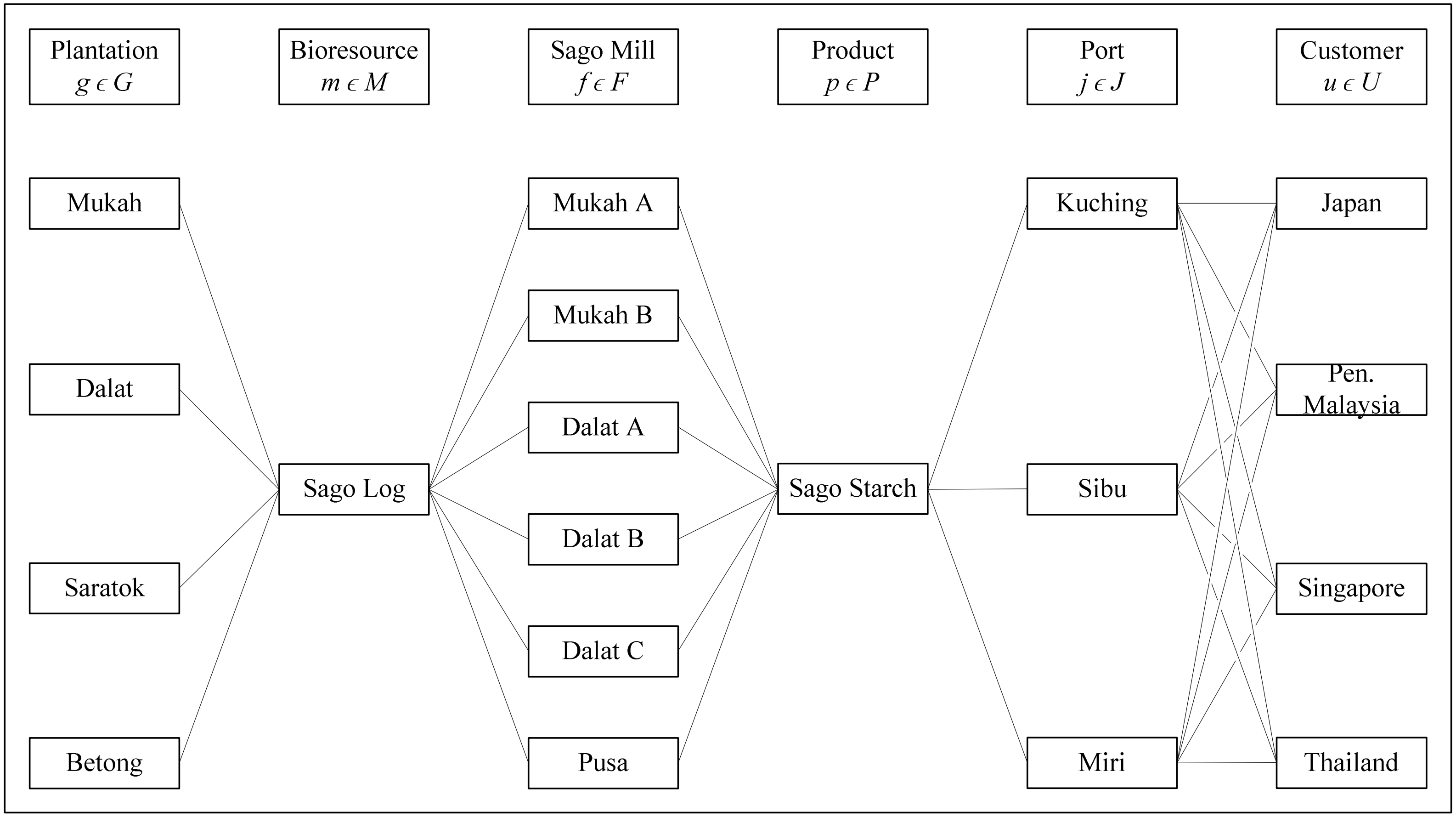

Figure 4.5: Superstructure of sago value chain

of sago-based product ($S_{g,p}$) are rewritten as $L_{g,\text{starch}}$ and $S_{g,\text{starch}}$, respectively. Equation (4.13) is re-formulated as:

$$S_{g,\text{starch}} = K_g^{\text{Plant}} V_{g,\text{Log}} L_{g,\text{starch}} \qquad \forall g \qquad (4.76)$$

In this case, $L_{g,\text{starch}}$ is given as a range of 0.015 – 0.025 ton of dry starch/log as shown in Table A1. Meanwhile, K_g^{Plant} is given as 100 palm/ha.y and $S_{g,p}$ is computed to be in the range of 15 – 25 ton of dry starch/ha.y. According to Bujang (2008), the amount of starch per log is estimated as 20% of the fresh weight of each log. Hence, the conversion rate of log to product in sago mills f ($V_{f,p}$), which is rewritten as $V_{f,\text{starch}}$ (conversion rate of log to starch) for each sago mill, is 0.2. In addition, Equation (4.11) can be reformulated as:

$$X_{f,\text{starch}}^{\text{ProSys}} = \sum_g W_{g,f}^{\text{Plant\_ProSys}} V_{f,\text{starch}} \qquad \forall f \qquad (4.77)$$

On the other hand, $D_{p,u}^{\text{UL}}$ and $D_{p,u}^{\text{LL}}$ are also rewritten as $D_{\text{starch},u}^{\text{UL}}$ and $D_{\text{starch},u}^{\text{LL}}$, respectively. These data are given in Table 1 as well and Equation (4.25) is rewritten as:

$$D_{\text{starch},u}^{\text{LL}} \le \sum_j X_{\text{starch},j,u}^{\text{Port\_Cust}} \le D_{\text{starch},u}^{\text{UL}} \qquad \forall u \qquad (4.78)$$

where $X_{\text{starch},j,u}^{\text{Port\_Cust}}$ is the total amount of starch that is delivered from port j to customer u.

In this case study, plantations which are located in Mukah, Dalat, Saratok and Betong are taken into consideration. Meanwhile, sago mills which are located in those districts are identified as the processing facilities (Mukah A, Mukah B, Dalat A, Dalat B, Dalat C and Pusa). In addition, for all road transportation, lorries, each with a capacity (Z^{Lorry}) of 10 t are used in this case study. The map of Sarawak, Malaysia (Google Maps, 2014) is illustrated in Figure 4.6. As shown, there are different districts that need to be traversed to reach the sago mills or ports. For instance, in order to send sago logs from Saratok plantation to Mukah A, a lorry needs to pass through the Saratok, Sarikei, Maradong, Sibu, Dalat and Mukah districts, with actual travel distances as summarised in Table (A2) – (A3) (see Appendix A). For the delivery of sago starch to customers via sea transportation, twenty-foot containers, each with a capacity, Z^{TEU}, of 20 ton are used in this case. The distances between ports and customer ports are shown in Table A4 in the Appendix A of this thesis.

On the other hand, in order to determine the economic potential of this value chain, unit costs of harvesting, processing, port handling, road transportation and sea transportation, as well as selling prices of sago logs and sago starch, are all estimated based on the information provided by the sago mill owners. These data are summarised in Table A5 (see Appendix A). To determine the total WPFP, harvesting risk, processing risk, handling risk, road and sea transportation risks are first estimated based on reliable data as shown in Table A6 (see Appendix A). In this case, risks are estimated based on the occupational accidents statistics published by

Figure 4.6: Route map illustration of Sarawak, Malaysia

the Department of Occupational Safety and Health (DOSH, 2013a; DOSH, 2013b) and casualty statistics published by the International Maritime Organisation (IMO, 2012).

In addition, the emission factor (EF) of power generation is needed to determine the total power-based CFP of the sago value chain. In this case study, the grid power mix is used in this sago value chain to support value chain activities. Therefore, EF^{Power} in Equation (4.39) is replaced by the emission factor of grid power, EF^{Grid}. Based on the power (PW_{pp}) generated by the individual power plant and the emission factor (EF_{pp}) of each power plant, as shown in Table A7 (see Appendix A), EF^{Grid} is determined via:

$$EF^{Grid} = \frac{\sum_{pp}\left[PW_{pp} EF_{PP}\right]}{\sum_{pp} PW_{pp}} \tag{4.79}$$

By solving the equation above, EF^{Grid} is determined as 0.8990 kg CO_2/kWh.

To determine fuel-based CFP, EF^{Fuel_Road} and EF^{Fuel_Sea} are given in Table A7. Based on the given data in Tables A1 – A4 and A7 as well as the power consumption of each sago mill in Table A8 in Appendix A, the total CFP of the sago value chain can be determined via Equations (4.3) – (4.25) and Equations (4.37) – (4.43).

Meanwhile, the total WFP of the sago value chain can be determined based on the total volume of inlet water and PWR as well as the contaminant concentration in the discharged water. These data are estimated for each sago mill and presented in Table A9 (see Appendix A). In addition, water required for power generation (WR^{Power}), road (WR^{Road}), and sea transportation (WR^{Sea}), can be determined via the following equations.

$$WR^{Power} = \frac{\sum_{pp}\left[PW_{pp} WR_{PP}\right]}{\sum_{pp} PW_{pp}} \quad (4.80)$$

$$WR^{Road} = TAWF \times ER^{Road}/1000 \quad (4.81)$$

$$WR^{Road} = TAWF \times ER^{Sea}/1000 \quad (4.82)$$

where WR_{pp} is the required water for power generation in each power plant; TAWF is the total average water footprint for crude oil production with given value of 1.058 m^3/GJ (Gerbens-Leenes et al., 2008). Meanwhile, ER^{Road} and ER^{Sea} are the energy requirements for lorry and ship transport mode where ER^{Road} = 2.3 MJ/km-t and ER^{Sea} = 0.095 MJ/km-t (Gerbens-Leenes and Hoekstra, 2011). By solving Equations (4.80) – (4.82), WR^{Power}, WR^{Road}, and WR^{Sea} can be determined and the results are summarised in Table A8. Based on the data in Table A7 – A9, the total WFP of the sago value chain is determined via Equations (4.3) – (4.25), Equations (4.26) – (4.36) and Equations (4.80) – (4.82).

Following with the proposed approach, the proposed fuzzy model is a mixed integer linear programming (MILP) model (Equations (4.3) – (4.75)), which is then solved with each optimisation objective to determine the respective upper and lower fuzzy limits. In this case study, the upper and lower fuzzy limits can be predetermined by solving the objectives individually (i.e., maximise *TotEP*, minimise $TotR^{D}$, minimise $TotR^{NPD}$, minimise $TotR^{PD}$, minimise *TotCFP*, and minimise *TotWFP*), without considering their mutual interactions. This individual optimisation allows the best (upper limit) and worst values (lower limit) of each objective to be determined. The optimisation results of each individual objective are summarised in Table 4.1. The maximum and minimum values of the respective optimisation objectives are selected as upper and lower limits, respectively. These limits are highlighted in boldface in Table 4.1. As shown, the limits of *TotEP* are determined as 5.732×10^{7} MYR/y and 3.341×10^{7} MYR/y, respectively. For $TotR^{D}$, $TotR^{NPD}$ and $TotR^{PD}$, the upper limits are determined as 0.047 deaths/y, 0.378 NPD/y and 0.014 PD/y, respectively. Meanwhile, 0.012 of deaths/y, 0.093 of NPD/y and 0.004 of PD/y are determined as lower limit of $TotR^{D}$, $TotR^{NPD}$ and $TotR^{PD}$, respectively. Besides, the upper and lower limits of *TotCFP* are 1.725×10^{7} $kgCO_2$/y and 1.250×10^{7} $kgCO_2$/y, respectively. Meanwhile, 1.368×10^{8} m^3/y and 1.206×10^{8} m^3/y are the upper and lower limit of *TotWFP*, respectively.

Based on the upper and lower fuzzy limits and the given data in Tables A1 – A9, the optimisation model is solved via LINGO 13.0 in an ASUS K46C with Intel® Core™ i5-3317U (1.70GHz) and 6.00 GB RAM under a 64-bit operating system computer.

The CPU time to obtain the global optimal solution was approximately within 5 seconds. An optimum sustainable sago value chain with maximum λ of 0.682 is determined. The maximum total profit of 4.973×10^7 MYR/y, minimum death risk of 0.023 deaths/y, minimum NPD risk of 0.180 NPD/y, minimum PD risk of 0.007 PD/y, minimum CFP of 1.332×10^7 kgCO_2/y and minimum WFP of 1.257×10^8 m^3/y are determined as summarised in the last row of Table 4.1. Note that the resulting power-based and fuel-based water footprint is not significant comparing with green and grey water footprint. On the other hand, in the aspect of workplace footprint, a comparison table is showed in Table 4.2 to analyse the significance of risks in affecting the optimum value chain. As shown, a total of 39.5%, 39.6%, and 36.4% of death (D), non permanent disability (NPD), and permanent disability (PD) risks can be reduced respectively in the optimum case (Max. λ) compare with the case with maximum total economic performance (Max. *TotEP*). Therefore, to synthesise a sustainable value chain, those risks are required to be considered. In addition, the details of mass flowrates are shown in the last column of Tables 4.3 – 4.5. Besides, these tables also included the mass flowrate based on the specific optimisation objectives.

Based on the optimised results, only the sago logs from Mukah and Saratok plantations are sent to sago mills for sago starch production, with a total amount of 3,839,000 logs/y and 761,000 logs/y, respectively (see last column of Table 4.3). Sago logs from Dalat and Betong plantations do not supplied to sago mills due to the long distance between Betong plantation and sago mills. Besides, it also due to the high harvesting risk of Dalat plantation. On the other hand, the starch is then sent to Kuching and Sibu port for storage and then delivered to the customers (Japan, Peninsular Malaysia, Singapore and Thailand). Each port receives 18,920 t/y and 27,080 t/y, of starch, respectively (Table 4.4). Based on the result, the starch does not sent to Miri port because the distance between sago mills and Miri port is far. Besides, high transportation risk in Miri is observed. Note that all the starch that was received by the Kuching port is then delivered to Peninsular Malaysia. On the other hand, Sibu port delivers 12,500 t/y, 11,080 t/y, 2,500 t/y and 1,000 t/y of starch to Japan, Peninsular Malaysia, Singapore and Thailand, respectively (Table 4.5). This optimal configuration of a sustainable sago value chain is shown in Figure 4.7.

Table 4.1: Results of maximisation of TotEP, minimisation of $TotR^D$, $TotR^{NPD}$, $TotR^{PD}$, TotCFP and TotWFP

Objective Functions	*TotEP* x 10^7 (MYR/y)	$TotR^{D}$ (Death/y)	$TotR^{NPD}$ (NPD/y)	$TotR^{PD}$ (PD/y)	*TotCFP* x 10^7 ($kgCO_2$/y)	*TotWFP* x 10^8 (m^3/y)
Max. *TotEP*	***5.732*** (EP^{UL})	0.038	0.298	0.011	1.306	1.307
Min. $TotR^{D}$	3.341	***0.012*** (R^{D_LL})	0.093	0.004	1.725	1.368
Min. $TotR^{NPD}$	3.341	0.012	***0.093***(R^{NPD_LL})	0.004	1.725	1.368
Min. $TotR^{PD}$	*3.341*(EP^{LL})	0.012	0.093	***0.004***(R^{PD_LL})	*1.725*(CFP^{UL})	*1.368* (WFP^{UL})
Min. *TotCFP*	5.372	0.035	0.276	0.010	***1.250*** (CFP^{LL})	1.244
Min. *TotWFP*	5.175	*0.047*(R^{D_UL})	*0.378*(R^{NPD_UP})	*0.014*(R^{PD_UL})	1.290	***1.206*** (CFP^{LL})
Max. λ = 0.682	4.973	0.023	0.180	0.007	1.332	1.257

** Note that 1 MYR is given as 0.30 USD.*

Table 4.2: Comparison results with optimum case

Objective Functions	$TotEP$ x 10^7 (MYR/y)	$TotR^{D}$ (Death/y)	$TotR^{NPD}$ (NPD/y)	$TotR^{PD}$ (PD/y)	$TotCFP$ x 10^7 ($kgCO_2$/y)	$TotWFP$ x 10^8 (m^3/y)
Max. $TotEP$	-13.2%	-39.5%	-39.6%	-36.4%	+2.0%	-3.8%
Min. $TotR^{D}$	+48.8%	+91.7%	+93.5%	+75.0%	-22.8%	-8.1%
Min. $TotR^{NPD}$	+48.8%	+91.7%	+93.5%	+75.0%	-22.8%	-8.1%
Min. $TotR^{PD}$	+48.8%	+91.7%	+93.5%	+75.0%	-22.8%	-8.1%
Min. $TotCFP$	-7.4%	-34.3%	-34.8%	-30.0%	+6.6%	+1.0%
Min. $TotWFP$	-3.9%	-51.1%	-52.4%	-50.0%	+3.3%	+4.2%

Table 4.3: Mass flowrate of selected routes from plantations to sago mills with objective function of maximise TotEP, minimise $TotR^{D}$, minimise $TotR^{NPD}$, minimise $TotR^{PD}$, minimise TotCFP, minimise TotWFP, and maximise λ.

Mass Flowrate (million logs/y)	Objective Functions						
	Max. *TotEP*	Min. $TotR^{D}$	Min. $TotR^{NPD}$	Min. $TotR^{PD}$	Min. *TotCFP*	Min. *TotWFP*	Max. λ
Mukah – Mukah A	1.320	0	0	0	1.320	0	1.320
Mukah – Mukah B	0.825	0	0	0	0.825	0	0.508
Mukah – Dalat A	0	0	0	0	0	0	0.726
Mukah – Dalat B	0	0	0	0	0	0	0.460
Mukah – Dalat C	0	0	0	0	0	0	0.825
Dalat – Mukah A	0	0	0	0	0	1.320	0
Dalat – Mukah B	0	0	0	0	0	0.508	0
Dalat – Dalat A	0.726	0	0	0	0.726	0.726	0
Dalat – Dalat B	0.825	0	0	0	0.825	0.825	0
Dalat – Dalat C	0.825	0	0	0	0.508	0.825	0
Dalat - Pusa	0	0	0	0	0	0.396	0
Saratok – Mukah A	0	1.320	1.320	1.320	0	0	0
Saratok – Mukah B	0	0.825	0.825	0.825	0	0	0
Saratok – Dalat B	0	0.463	0.463	0.463	0	0	0.365
Saratok – Dalat C	0	0.825	0.825	0.825	0	0	0
Saratok – Pusa	0.279	0	0	0	0.396	0	0.396
Betong – Dalat A	0	0.726	0.726	0.726	0	0	0
Betong – Dalat B	0	0.362	0.362	0.362	0	0	0
Betong – Pusa	0	0.079	0.079	0.079	0	0	0

Table 4.4: Mass flowrate of selected routes from sago mills to ports with objective function of maximise TotEP, minimise $TotR^{D}$, minimise $TotR^{NPD}$, minimise $TotR^{PD}$, minimise TotCFP, minimise TotWFP, and maximise λ.

Mass Flowrate (kt/y)	Objective Functions						
	Max. *TotEP*	Min. $TotR^{D}$	Min. $TotR^{NPD}$	Min. $TotR^{PD}$	Min. *TotCFP*	Min. *TotWFP*	Max. λ
Mukah A – KCH	0	13.20	13.20	13.20	0	0	6.71
Mukah A – SB	13.20	0	0	0	13.20	13.20	6.49
Mukah B - KCH	0	8.25	8.25	8.25	0	0	0
Mukah B - SB	8.25	0	0	0	8.25	5.08	5.08
Dalat A – KCH	0	7.26	7.26	7.26	0	0	0
Dalat A – SB	7.26	0	0	0	7.26	7.26	7.26
Dalat B – KCH	0	8.25	8.25	8.25	0	0	0
Dalat B – SB	8.25	0	0	0	8.25	8.25	8.25
Dalat C – KCH	0	8.25	8.25	8.25	0	0	8.25
Dalat C – SB	8.25	0	0	0	5.08	8.25	0
Pusa – KCH	0	0.79	0.79	0.79	0	0	3.96
Pusa – SB	2.79	0	0	0	3.96	3.96	0

Table 4.5: Mass flowrate of selected routes from ports to customers with objective function of maximise TotEP, minimise TotR^{D}, minimise TotR^{NPD}, minimise TotR^{PD}, minimise TotCFP, minimise TotWFP, and maximise λ.

Mass Flowrate (kt/y)	Objective Functions						
	Max. *TotEP*	Min. $TotR^{D}$	Min. $TotR^{NPD}$	Min. $TotR^{PD}$	Min. *TotCFP*	Min. *TotWFP*	Max. λ
KCH - Japan	0	12.50	12.50	12.50	0	0	0
KCH – P. Malaysia	0	30.00	30.00	30.00	0	0	18.92
KCH – Singapore	0	2.50	2.50	2.50	0	0	0
KCH – Thailand	0	1.00	1.00	1.00	0	0	0
SB - Japan	13.00	0	0	0	12.50	12.50	12.50
SB – P. Malaysia	30.70	0	0	0	30.00	30.00	11.08
SB – Singapore	3.00	0	0	0	2.50	2.50	2.50
SB – Thailand	1.30	0	0	0	1.00	1.00	1.00

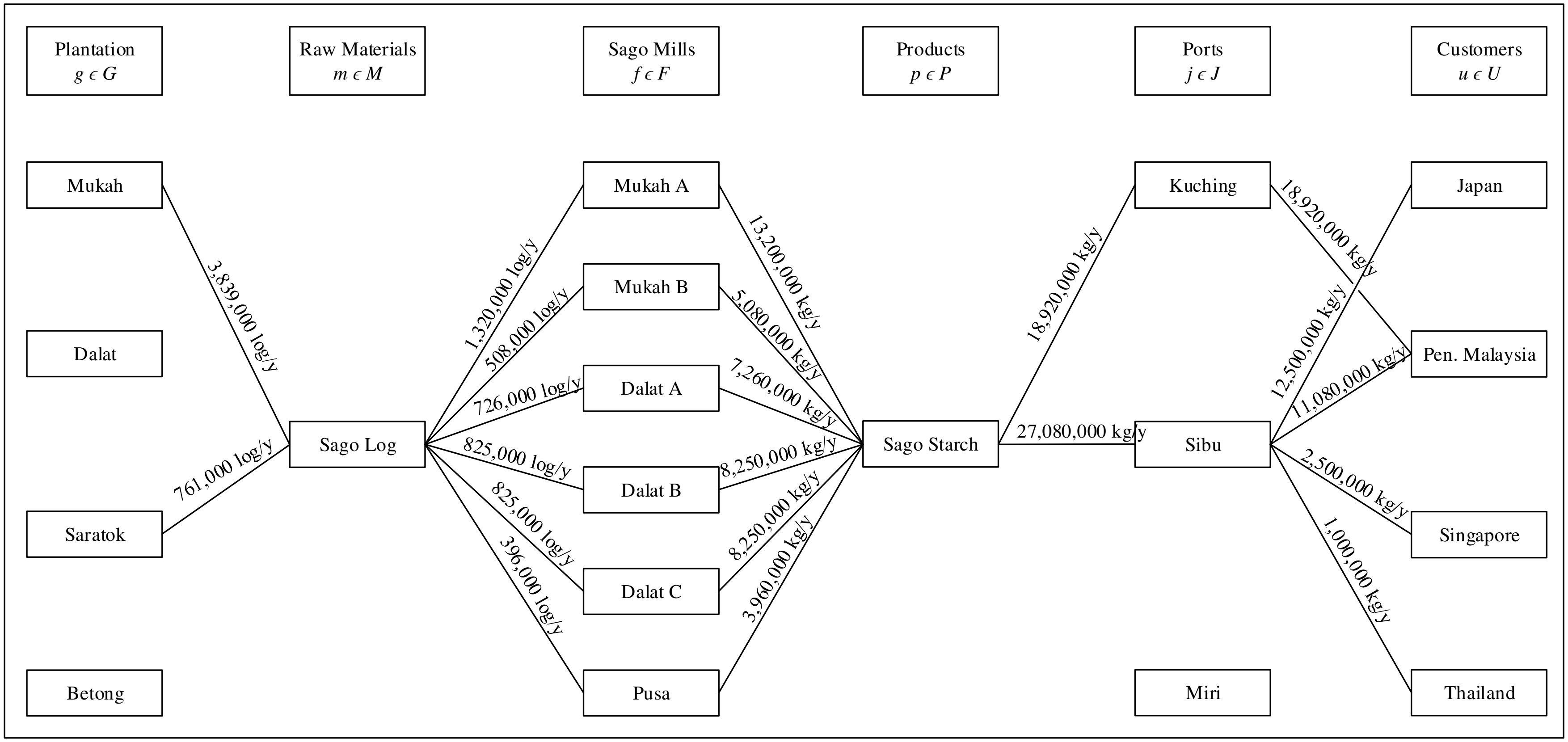

Figure 4.7: Optimal configuration of a sustainable sago value chain

4.1 Summary

Fuzzy Multi-Footprint Optimisation (FMFO), which considered carbon footprint, water footprint, workplace footprint, and economic performance simultaneously, to synthesis a sustainable sago value chain has been developed in this chapter. The proposed approach adopted the concept of fuzzy optimisation to trade-off the conflicts among the optimisation objectives and to determine the optimal sustainable sago value chain. Via fuzzy optimisation approach, the environmental impact and risks can be included as part of the optimisation objective and not as constraint to avoid any bias weighting factor that need to be predefined. This proposed approach can be used as an analysis tool that aids decision makers in pathway selection with multiple objective functions, so that the economic performance of the sago value chain can be maximised while environmental impacts and risks can be minimised simultaneously.

CHAPTER 5

MATERIAL FLOW COST ACCOUNTING (MFCA)-BASED APPROACH FOR PRIORITISATION OF WASTE RECOVERY

5.1 Introduction

As mentioned in Chapter 2, waste recovery has become one of the most important strategies to reduce environmental issues and improve economic performance in industry. Thus, different systematic approaches have been developed for waste recovery. However, most of the developed waste recovery approaches do not account for the cost of waste streams incurred from various processing steps as a criterion for prioritisation of waste recovery. This aspect can be determined by the concept of Material Flow Cost Accounting (MFCA), as presented in Section 2.5 of Chapter 2. Hence, in this chapter, a novel MFCA-based approach is developed for prioritisation of waste recovery with consideration of cost associated with waste streams. A case study is solved to illustrate the developed approach.

5.2 Problem Statement

The problem definition for the prioritisation of waste recovery in manufacturing process is stated as follows: Given a number of processes $i \in I$ in a specific boundary system generate intermediates $k \in K$, products $p \in P$ and wastes $w \in W$ as shown in Figure 5.1. In order to prioritise the waste streams for recovery, a novel MFCA-based approach is introduced in this thesis. The hidden cost of process i ($Cost_i^{HC}$) can be determined by quantifying the wastes in process i in monetary units. The objective is to determine the target or benchmark for the minimum total hidden cost of discharged waste ($Cost^{THC,Y'}$) of the specific boundary system.

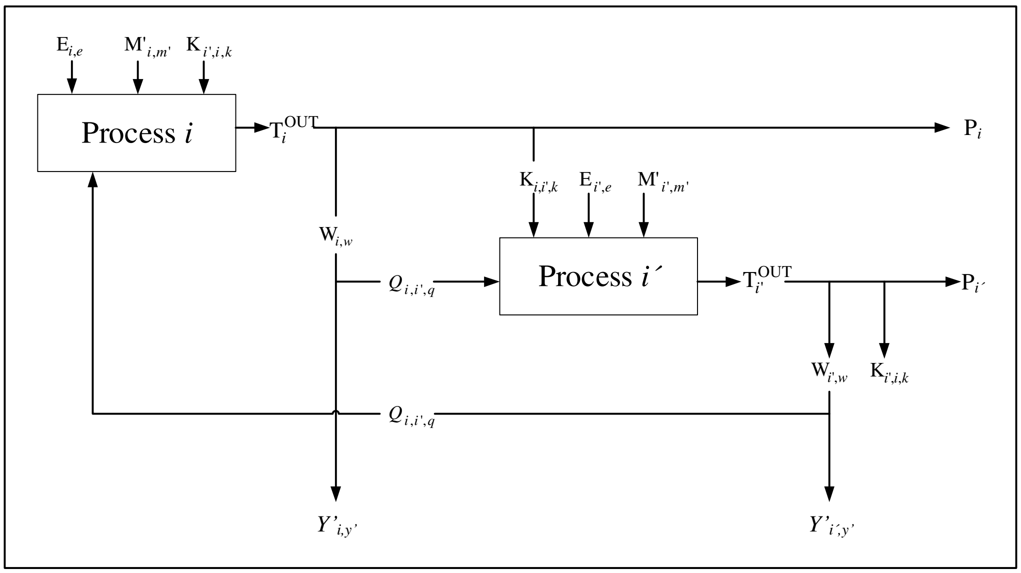

Figure 5.1: Generic process flow diagram for a manufacturing process

5.3 Formulation of MFCA-based Approach

5.3.1 Mass Balances

In a typical manufacturing process (see Figure 5.1), required amount of energy types e, $E_{i,e}$, raw materials m', $M_{i,m'}$, intermediate material k from process i', $K_{i',i,k}$, or recycled wastes q from process i', $Q_{i',i,q}$ are fed into process i to produce desired amount of intermediate material k for process i', $K_{i,i',k}$, and the desired amount of products p, $P_{i,p}$. Meanwhile, a total amount of wastes w, $W_{i,w}$ are generated during the process i. To determine the total output of process i, T_i^{OUT}, Equation (5.1) is given.

$$T_i^{OUT} = \sum_{i'} \sum_{k} K_{i,i',k} + \sum_{p} P_{i,p} + \sum_{w} W_{i,w} \qquad \forall i \qquad (5.1)$$

Since the waste can be recovered, the wastes of process i are divided into recycled waste q from process i to process i', $Q_{i,i',q}$ and discharged waste y', $Y'_{i,y'}$ as shown as:

$$\sum_{w=1}^{W} W_{i,w} = \sum_{i'} \sum_{q} Q_{i,i',q} + \sum_{y'} Y'_{i,y'} \qquad \forall i \qquad (5.2)$$

5.3.2 Cost Computation

Hidden cost (HC) consists of processing cost (PC) and carry-forward cost (CFC) as given as:

$$Cost_i^{HC} = Cost_i^{PC} + Cost_i^{CFC} \qquad \forall i \qquad (5.3)$$

where $Cost_i^{HC}$ and $Cost_i^{PC}$ are the hidden cost and the processing cost of process i, respectively; while, $Cost_i^{CFC}$ is carry-forward cost to process i. In this thesis, CFC is identified as the cost that is carried by recycled waste or intermediate material to process *i* as shown in Equations (5.8) – (5.11). As a result, cost accumulates over a sequence of successive processing steps. Note that $\text{Cost}_i^{\text{PC}}$ is composed of material costs, $\text{Cost}_i^{\text{MAT}}$, energy costs, $\text{Cost}_i^{\text{ENGY}}$, and system costs, $\text{Cost}_i^{\text{SYM}}$ as given as:

$$\text{Cost}_i^{\text{PC}} = \text{Cost}_i^{\text{MAT}} + \text{Cost}_i^{\text{ENGY}} + \text{Cost}_i^{\text{SYM}} \qquad \forall i \tag{5.4}$$

In this thesis, $\text{Cost}_i^{\text{MAT}}$ refers to the cost of raw material *m'* that is required in process *i* and can be determined via:

$$\text{Cost}_i^{\text{MAT}} = \sum_{m'} \text{UCost}_{i,m'} \text{M}_{i,m'} \qquad \forall i \tag{5.5}$$

where $\text{UCost}_{i,m'}$ is the unit cost of raw materials *m'*, and $\text{M}_{i,m'}$ is the required amount of raw material *m'* in process *i*. Likewise, $\text{Cost}_i^{\text{ENGY}}$ can be determined via:

$$\text{Cost}_i^{\text{ENGY}} = \sum_{e} \text{UCost}_{i,e} \text{E}_{i,e} \qquad \forall i \tag{5.6}$$

where $\text{UCost}_{i,e}$ is the unit cost of energy types *e*, and $\text{E}_{i,e}$ is the amount of energy types *e* required in process *i*. Besides, manpower cost is taken as $\text{Cost}_i^{\text{SYM}}$ and it is given as:

$$\text{Cost}_i^{\text{SYM}} = \sum_l \text{UCost}_{i,l}\text{L}_{i,l} \qquad \forall i \qquad (5.7)$$

where $\text{UCost}_{i,l}$ is the unit cost of manpower *l*, and $\text{L}_{i,l}$ is the required manpower *l* involved in process *i*, and index *l* represents the categories of manpower (i.e. local, foreign, etc.).

On the other hand, $Cost_i^{\text{CFC}}$ is divided into two sub-categories which are intermediate materials costs ($Cost_{i',i,k}$) and recycled waste material costs ($Cost_{i',i,q}$) from process *i'* to process *i*, as given as:

$$Cost_i^{\text{CFC}} = \sum_{i'}\sum_k Cost_{i',i,k} + \sum_{i'}\sum_q Cost_{i',i,q} \qquad \forall i \qquad (5.8)$$

Note that the intermediate material that required in process *i* ($\text{K}_{i',i,k}$), is also known as an intermediate product of process *i'*. Since $\text{K}_{i',i,k}$ is produced in process *i'*, it carries part of processing cost of process *i'*. To determine the intermediate material cost of process *i* ($Cost_{i',i,k}$), the hidden unit cost (HUC) of process *i'* is first to be determined via:

$$Cost_{i'}^{\text{HUC}} = Cost_{i'}^{\text{HC}} \big/ \text{T}_{i'}^{\text{OUT}} \qquad \forall i' \qquad (5.9)$$

where $Cost_{i'}^{\mathrm{HUC}}$, $Cost_{i'}^{\mathrm{HC}}$, and $\mathrm{T}_{i'}^{\mathrm{OUT}}$ are the HUC, HC, and total output of process *i'*, respectively. By multiplying the HUC of process *i'* ($Cost_{i'}^{\mathrm{HUC}}$) with the amount of intermediate material to process *i* ($\mathrm{K}_{i',i,k}$), the intermediate material cost of process *i* can be determined as given as:

$$\sum_{i'=1}\sum_{k=1} Cost_{i',i,k} = \sum_{i'=1}\sum_{k=1} Cost_{i'}^{\mathrm{HUC}} \mathrm{K}_{i',i,k} \qquad \forall i \qquad (5.10)$$

where $\sum_{i'}\sum_{k} Cost_{i',i,k}$ is the total intermediate materials cost of process *i*. Similarly, to determine total recycled waste material cost of process *i* ($Cost_{i',i,q}$), the amount of recycled waste to process *i* ($Q_{i',i,q}$) is multiplied by HUC as given as:

$$\sum_{i'}\sum_{q} Cost_{i',i,q} = \sum_{i'}\sum_{q} Cost_{i'}^{HUC} Q_{i',i,q} \qquad \forall i \qquad (5.11)$$

where $\sum_{i'}\sum_{q} Cost_{i',i,q}$ is the total recycled waste material cost of process *i*. By solving Equations (5.1) – (5.2) and Equations (5.4) – (5.11), both PC ($\mathrm{Cost}_i^{\mathrm{PC}}$) and CFC ($Cost_i^{\mathrm{CFC}}$) of process *i* can be determined. Then, HC of process *i* ($Cost_i^{\mathrm{HC}}$) can be found via Equations (5.3). Next, these HC can be allocated to the product and waste materials of process *i* according to the materials distribution percentage (usually mass basis) to determine both HC of products and wastes via:

$$Cost_{i,p}^{\mathrm{HC}} = Cost_{i}^{\mathrm{HUC}} \ \mathrm{P}_{i,p} \qquad \forall i \forall p \qquad (5.12)$$

$$Cost_{i,w}^{\mathrm{HC}} = Cost_{i}^{\mathrm{HUC}} \ \mathrm{W}_{i,w} \qquad \forall i \forall w \qquad (5.13)$$

where $Cost_{i,p}^{\mathrm{HC}}$ is the HC of product and $Cost_{i,w}^{\mathrm{HC}}$ is the HC of waste of process *i*. The HC of discharged waste of process *i* ($Cost_{i}^{\mathrm{HC,Y'}}$) is given as:

$$Cost_{i}^{\mathrm{HC,Y'}} = \left[\sum_{y'} Cost_{i}^{\mathrm{HUC}} \ Y'_{i,y'}\right] + Cost_{i}^{\mathrm{MGT}} \qquad \forall i \qquad (5.14)$$

where $Cost_{i}^{\mathrm{MGT}}$ represents waste management cost of process *i* which can be determined via:

$$Cost_{i}^{\mathrm{MGT}} = \sum_{y'} \sum_{b} \mathrm{Cost}_{i,y',b} Y'_{i,y'} \left[\mathrm{QLT}_{i,y',b} - \mathrm{STD}_{b}\right] \quad \forall i \forall b \qquad (5.15)$$

where $\mathrm{Cost}_{i,y',b}$ is the waste discharge unit cost of discharged waste *y'* with contaminant *b* and $Y'_{i,y'}$ is the amount of discharged waste *y'* of process *i*. Meanwhile, $\mathrm{QLT}_{i,y',b}$ is the effluent waste quality of discharged waste *y'* with contaminant *b*, and $\mathrm{STD}_{i,b}$ is the standard discharge limit of contaminant *b*.

To determine the minimum total hidden cost (THC) of discharged waste, the total HCs of discharged waste from all processes are summed up as given as:

$$Cost^{\text{THC, Y'}} = \sum_i Cost_i^{\text{HC, Y'}} \tag{5.16}$$

Meanwhile, the waste stream to be recovered can be prioritised to determine minimum THC of discharged waste via:

$$\text{Minimise } Cost^{\text{THC,Y'}} \tag{5.17}$$

This model involved several bilinear terms and this causes the model become a non-linear program (NLP). In order to ensure global optimality, this model is solved via LINGO version 13 with global solver, a commercial optimisation software with a branch-and-bound based Global Optimization Toolbox (Gau and Schrage, 2004), in an ASUS K46C with Intel® Core™ i5-3317U (1.70GHz) and 6.00 GB RAM under a 64-bit operating system. The CPU time to obtain the global optimal solution was approximately one second. To illustrate the proposed model, a case study, sago starch extraction process (SSEP) with the objective of minimising total hidden cost (THC) of discharged waste is solved in Section 5.4.

5.4 Case Study

As shown in the process block diagram of SSEP (Figure 1.5 in Chapter 1), sago starch can be extracted from sago logs via debarking (DBK), rasping (RPG), fibre separation (FSEP), sieving (SIEV), starch water separation (SWSEP), filtration (FILT), drying and packing (DP) processes as well as water treatment process (WTP). The process block diagram of SSEP is further extended in this chapter by adding in the material flow as shown in Figure 5.2. The material flow of SSEP is deduced from the information given by industry partners, as well as Adeni et al. (2009), Bujang (2008), Singhal et al. (2008), and Vikineswary et al. (1994).

As shown in Figure 5.2, large amount of water is required from WTP during the processes of RPG, FSEP and SIEV. Meanwhile, the wastes such as sago bark are generated from DBK process, combined wastewater and sago fibre are generated during FSEP and SIEV processes, and wastewater is generated during SWSEP and FILT processes.

The wastewater generated from sago starch processing highlighted in Figure 5.2 (dashed line) is mixed with the river water before send to RGP, FSEP and SIEV processes. In this case, the wastewater stream of FSEP, SIEV, SWSEP and FILT processes are identified as the potential water sources to be recovered. To illustrate the prioritisation of waste recovery, wastewater is recovered to WTP based on different RP. Besides, the amount of desired products, intermediate products, wastes, and total output of this case study are summarised in Table 5.1. The amount and unit cost of required raw material, energy and labour as well as the wastes generated from each sago starch process is tabulated in Table 5.2. It is assumed that the cost of river water (USD 0.33 / m^3) is the same as commercial water rate in Sarawak, Malaysia.

Based on the information given in Table 5.2, total cost of processing, raw materials, energy, and system of each sago starch process are determined in Table 5.3 via Equations (5.4) – (5.7). The waste disposal cost of this case study is determined via Equation (5.15) based on the given discharged waste quality and the limitation discharged quality (standard A) as shown in Table 5.4.

Table 5.1: Mass flowrate of desired products, intermediate products, wastes and total output of each sago starch extraction process

Process	Desired Product, P_i (t)	Wastes, W_i (t)			Intermediate Product, $\sum_{i'} K_{i,i'}$ (t)	Total Output, T_i^{out} (t)
		Bark	Wastewater	Fibre		
WTP	0	0	0	0	243.0	243.0
DBK	0	20.8	0	0	62.4	83.2
RPG	0	0	0	0	98.4	98.4
FSEP	0	0	79.0	15.1	91.3	185.4
SIEV	0	0	119.4	1.8	90.1	211.3
SWSEP	0	0	59.7	0	30.4	90.1
FILT	0	0	17.9	0	12.5	30.4
DP	12.0	0	0	0	0	12.0

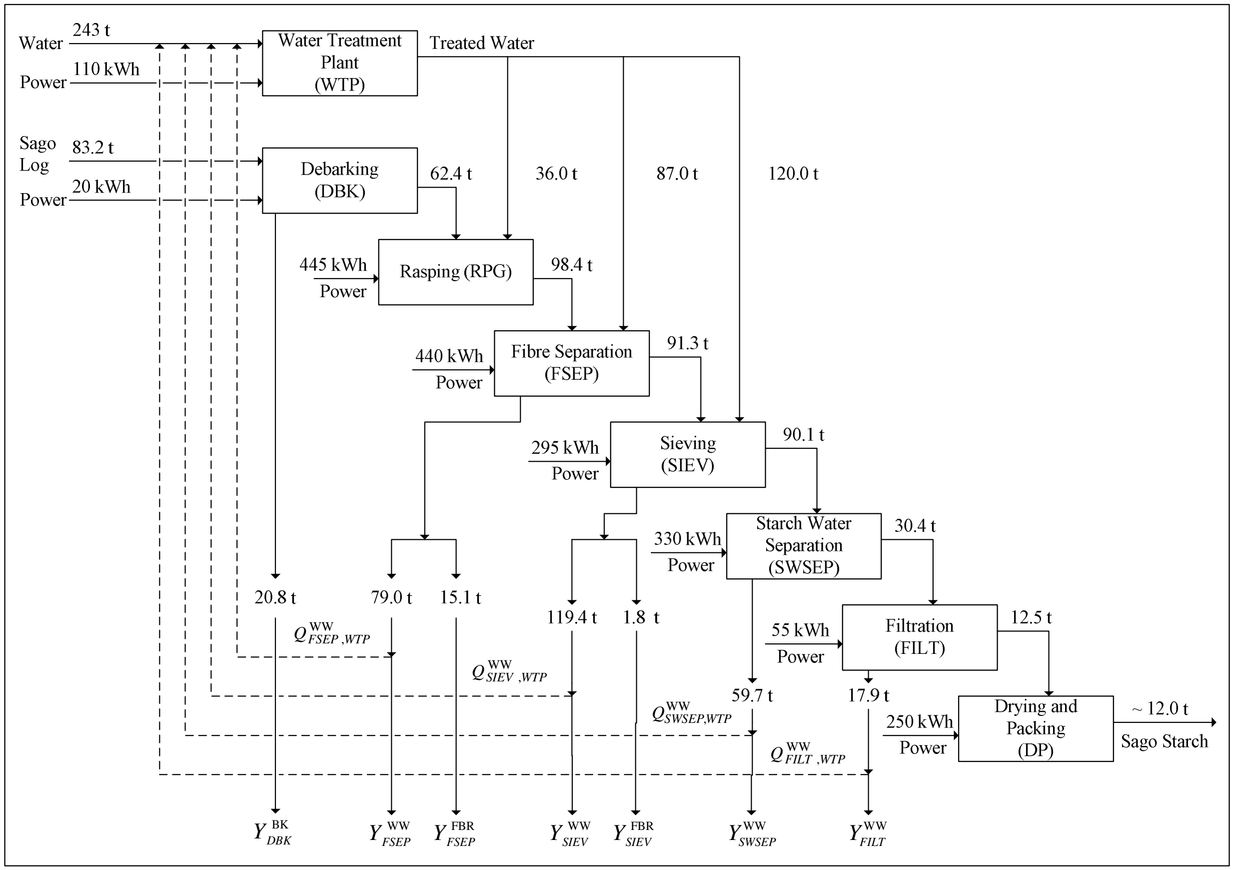

Figure 5.2: Process block diagram of sago starch extraction process (SSEP)

Table 5.2: Required raw materials, energy, manpower, and generated wastes of each sago starch extraction process, and unit costs

	Processes of Sago Starch Production								Unit Costs (USD)
	WTP	DBK	RPG	FSEP	SIEV	SWSEP	FILT	DP	
Raw Materials:									
Water (t)	243	0	0	0	0	0	0	0	0.33 / m^3
Sago Logs (log)	0	832	0	0	0	0	0	0	2.80 / log
(100 kg/log)		(83.2 t)							
Energy:									
Electricity (kWh)	110	20	445	440	295	330	55	250	0.11 / kWh
Manpower:									
Local (person)	1	3	6	1	1	1	1	3	8.00 / day
Wastes:									
Bark (t)	0	20.8	0	0	0	0	0	0	0
Wastewater (t)	0	0	0	71.1	124.1	57.9	22.3	0	0.02 / kg BOD
Fibre (t)	0	0	0	5.5	11.4	0	0	0	15.63 / kg NH_3-N

Table 5.3: Total processing, raw materials, energy, and system costs of each sago starch extraction process

	Processes of Sago Starch Production							
	WTP	DBK	RPG	FSEP	SIEV	SWSEP	FILT	DP
Water (USD)	80.2	0	0	0	0	0	0	0
Sago Logs (USD)	0	2329.6	0	0	0	0	0	0
Total Raw Material Cost (USD)	80.2	2329.6	0	0	0	0	0	0
Electricity (USD)	12.1	2.2	49.0	48.4	32.5	36.3	6.1	27.5
Total Energy Cost (USD)	12.1	2.2	49.0	48.4	32.5	36.3	6.1	27.5
Manpower (Local, USD)	8	24	48	8	8	8	8	24
Total System Cost (USD)	8	24	48	8	8	8	8	24
Processing Cost (USD)	100.3	2355.8	97.0	56.4	40.5	44.3	14.1	51.5

Table 5.4: Discharged wastes quality and discharge limitation quality (standard A) specified in Environment Quality Act 1979

Processes	Discharged Wastes Quality (ppm)	
	BOD	NH_3-N
FSEP	5,360.5	93.4
SIEV	2,497.0	43.5
SWSEP	2,534.4	44.2
FILT	2,816.0	49.1
	Discharge Limitation Quality (ppm)	
Standard A	BOD	NH_3-N
	20.0	10.0

Equations (5.1) – (5.17) are solved based on the information given in Tables 5.1 – 5.4 at different RP (0 – 88%) to prioritise the waste streams for recovery, while identifying the minimum THC of discharged waste. Note that, only 88% of the waste can be recovered in this case as only 243 m^3 of water is required in sago starch extraction process, while the total available wastewater is 276 m^3. It is also noted that the power consumption at different RP is not vary according to the flow rate of recycle water as the process flow and equipments used are remained unchanged. The results of prioritisation of waste recovery and the minimum THC of discharged waste at different RP are summarised in Figure 5.3 and Table 5.5. As shown in Figure 5.3, THC of discharged waste has an inverse relationship with RP. The wastewater from FSEP is first to be recovered and followed by FILT, SWSEP, and then SIEV, as shown in Table 5.5. Similarly, the detailed results for RP of 0%, 10%, 30%, 40%, 60%, and 88% are extracted and summarised in Tables 5.6 and 5.7 for further analysis.

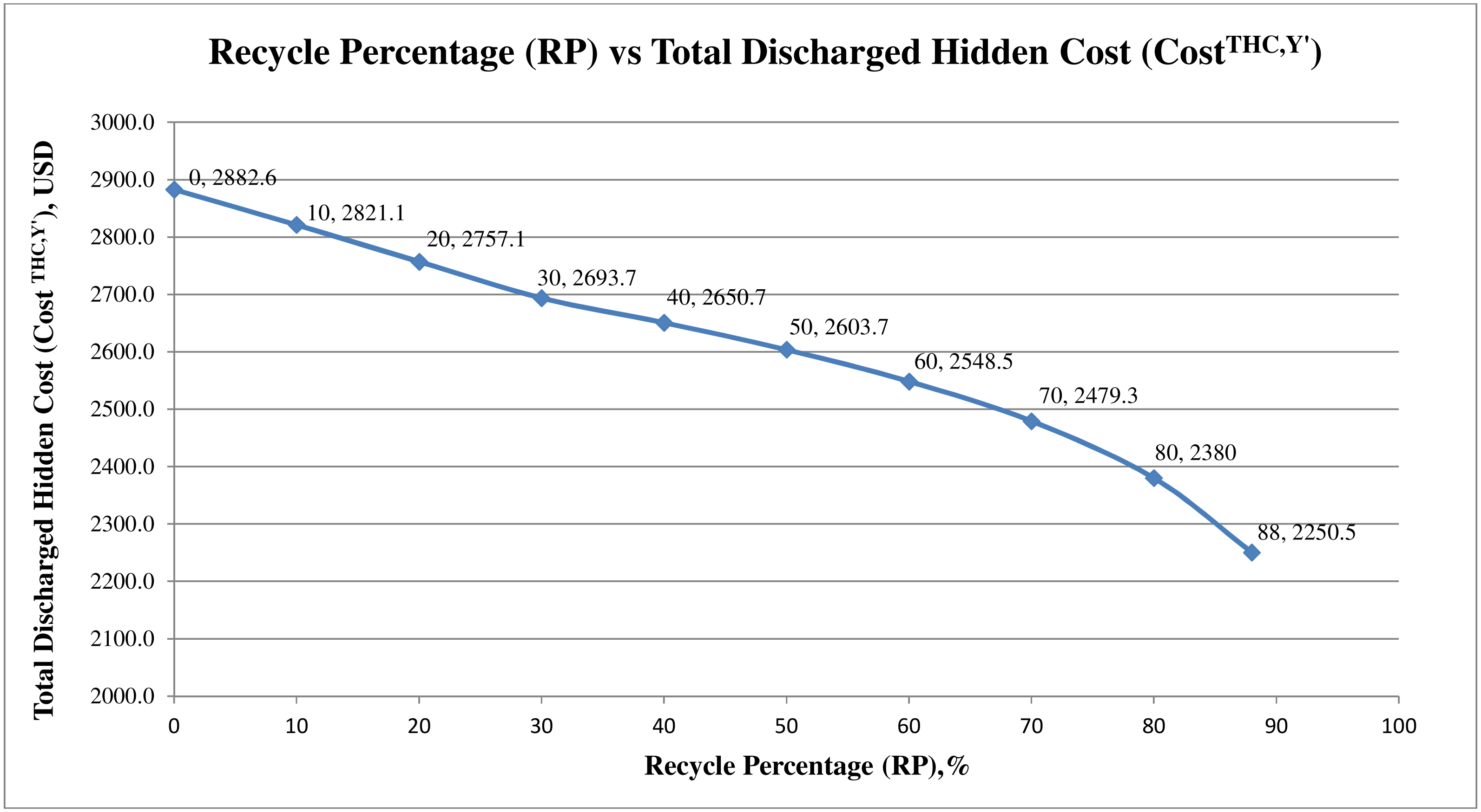

Figure 5.3: Recycle percentages versus total discharged hidden cost for a sago starch extraction process

Table 5.5: Prioritisation results with determined minimum total discharged hidden cost in different recycle percentages for sago starch extraction process

Recycle Percentage (RP, %)	Total Discharged Hidden Cost ($Cost^{THC,Y'}$) (USD)	Prioritisation of Waste Streams to be Recovered (t)
0	2882.7	N/A
10	2821.2	1) FSEP (27.6)
20	2757.1	1) FSEP (55.2)
30	2693.8	1) FSEP (79.0); 2) FILT (3.8)
40	2650.7	1) FSEP (79.0) ; 2) FILT (17.9) ; SWSEP (13.5)
50	2603.7	1) FSEP (79.0) ; 2) FILT (17.9) ; SWSEP (41.1)
60	2548.5	1) FSEP (79.0) ; 2) FILT (17.9) ; SWSEP (59.7); 4) SIEV (9.0)
70	2479.3	1) FSEP (79.0) ; 2) FILT (17.9) ; SWSEP (59.7); 4) SIEV (36.6)
80	2380.0	1) FSEP (79.0) ; 2) FILT (17.9) ; SWSEP (59.7); 4) SIEV (64.2)
88	2250.5	1) FSEP (79.0) ; 2) FILT (17.9) ; SWSEP (59.7); 4) SIEV (86.3)

Table 5.6: Hidden cost and total hidden cost of discharged waste, and hidden unit cost of each waste streams for sago starch extraction process

Processes	Hidden Unit Cost (USD/t)						Waste Management Cost (USD)						Hidden Cost of Discharged Waste (USD)					
RP (%)	0	10	30	40	60	88	0	10	30	40	60	88	0	10	30	40	60	88
DBK	28.3	28.3	28.3	28.3	28.3	28.3	0	0	0	0	0	0	589.0	589.0	589.0	589.0	589.0	589.0
FSEP	10.6	11.5	13.6	14.6	17.8	32.0	132.7	93.8	21.3	21.3	21.3	21.3	1133.1	856.6	226.5	242.1	290.6	504.6
FILT	6.0	7.1	9.7	11.1	15.3	33.5	11.9	11.9	9.4	0	0	0	118.9	138.2	147.3	0	0	0
SWSEP	5.5	6.6	9.3	10.6	14.8	33.0	34.9	34.9	34.9	27.0	0	0	363.9	428.5	591.4	519.0	0	0
SIEV	5.0	6.1	8.8	10.2	14.3	32.6	69.5	69.5	69.5	69.5	64.3	20.0	677.8	808.9	1139.6	1300.6	1668.9	1156.9
Total hidden cost (THC) of discharged waste (USD)													2882.7	2821.2	2693.8	2650.7	2548.5	2250.5

Table 5.7: Mass flowrate of available, recycled, and discharged wastes in different recycle percentages for sago starch extraction process

Processes	Available Waste, W_i^w (t)		Recycled Waste to WTP, $Q_{i,i'}^q$ (t)							Discharged Wastes, $Y'^{y'}_i$ (t)						
	WW	Fibre	WW						Fibre	WW						Fibre
RP (%)	0 - 100	0 - 100	0	10	30	40	60	88	0 - 100	0	10	30	40	60	88	0 - 100
FSEP	79.0	15.1	0	27.6	79.0	79.0	79.0	79.0	0	79.0	51.4	0	0	0	0	15.1
FILT	17.9	0	0	0	3.8	17.9	17.9	17.9	0	17.9	17.9	14.1	0	0	0	0
SWSEP	59.7	0	0	0	0	13.5	59.7	59.7	0	59.7	59.7	59.7	46.2	0	0	0
SIEV	119.4	1.8	0	0	0	0	9.0	86.3	0	119.4	119.4	119.4	119.4	110.4	33.1	1.8
Total	276.0	16.9	0	27.6	82.8	110.4	165.6	242.9	0	276.0	248.4	193.2	165.6	110.4	33.1	16.9

As shown in Table 5.6, THC of discharged waste at RP of 0%, 10%, 30%, 40%, 60%, and 88% are determined as USD 2,882.7, USD 2821.2, USD 2,693.8, USD 2,650.7, USD 2,548.5 and USD 2,250.5, respectively. In this case, the case with RP of 0% is taken as a base case, where no wastewater is recycled to WTP, and all the water that used in WTP is sourced from nearest river. As results, a total savings of USD 61.5, USD 188.9, USD 232.0, USD 334.2 and USD 632.2 are determined for RP of 10%, 30%, 40%, 60%, and 88%, respectively. Besides, for the case with RP of 0%, 10%, 30%, 40% and 60%, FSEP process possesses the highest HUC among other processes (i.e. SIEV, SWSEP and FILT), followed by the FILT, SWSEP, and SIEV processes. At these RPs, the waste streams are prioritised based on the order of HUC; that is, the waste stream possessing the highest HUC is prioritised for recovery, as shown in Table 5.7. As shown, FSEP is prioritised to be recovered and recycled to WTP, followed by FILT, SWSEP and SIEV.

However, there is an exceptional case at RP 88% where the prioritisation of waste recovery is not based on the order of HUC. As shown in Table 5.6, SIEV possesses higher HUC compared to FSEP. However, the wastewater from SIEV is not prioritised for recovery. Instead, all the wastewater from FSEP is recovered and sent to WTP, and only part of the wastewater from SIEV is recycled to the WTP, as shown in Table 5.7. This exceptional case shows that the prioritisation results are not always in the order of HUC. This effect can be explained by solving the model with wastewater from FILT, SWSEP, and SIEV (three highest HUC processes) being recovered fully to the WTP, and only part of the wastewater from FSEP being recovered to make up the required process water for RP of 88%. For comparison purposes, detailed results of both Scenario 1 (the wastewater from FSEP stream is fully recovered) and Scenario 2 (the wastewater from SIEV stream is fully recovered) are extracted and summarised in Table 5.8. As shown, the THC of discharged waste in Scenario 2 (USD 2,273.7) is higher than Scenario 1 (USD 2,250.5). Namely, the prioritisation of waste recovery is not based on the order of HUC to determine the minimum THC of discharged waste, but it is also affected by other factors. In this analysis (see Table 5.8), total CFC to WTP is found to increase from USD 7,911.2 (Scenario 1) to USD 8,010.4 (Scenario 2). This increased CFC leads to a higher CFC to each process, and thus subsequently caused higher HC and HUC of each process. This result shows that CFC is an important factor affecting the HUC in prioritisation for waste recovery. Aside from this, waste management cost is found to be another factor in determining the waste stream to be recovered. As shown in Table 5.8, the waste management cost of Scenario 2 (USD 69.0) is higher than Scenario 1 (USD 41.3). This higher cost has led to higher THC of discharged waste in Scenario 2. In other words, the amount and quality of discharged waste, which is the main factor to cause higher waste management cost, are important factors for prioritisation of waste recovery. Based on these findings, it can be seen that HUC, CFC, amount and quality of discharged waste all significantly affect the prioritisation results. Through the MFCA-based approach, these factors can be traded off to determine minimum THC of discharged waste.

Table 5.8: Detailed results of waste stream prioritisation of scenario 1 and 2 at RP of 88%

Processes	PC (USD)	CFC (USD)	HC (USD)	HUC (USD)	Waste to be Recycled (t)	CFC of Recycled Stream to WTP (USD)	Discharged Waste (t)				Waste Management Cost (USD)	HC of Discharged Waste (USD)
					WW		Bark	WW	Fibre	Total		
Scenario 1:												
DBK	2355.8	0	2355.8	28.3	0	0	20.8	0	0	20.8	0	588.6
FSEP	56.4	5878.2	5934.6	32.0	79.0	2528.0	0	0	15.1	15.1	21.3	504.5
FILT	14.1	1004.7	1018.8	33.5	17.9	599.7	0	0	0	0	0	0
SWSEP	44.3	2933.4	2977.7	33.0	59.7	1970.1	0	0	0	0	0	0
SIEV	40.5	6838.9	6879.4	32.6	86.3	2813.4	0	33.1	1.8	34.9	20.0	1157.4
Total	2511.1	16,655.2	19,166.3	159.4	242.9	7911.2	20.8	33.1	16.9	70.8	41.3	2250.5
Scenario 2:												
DBK	2355.8	0	2355.8	28.3	0	0	20.8	0	0	20.8	0	588.6
FSEP	56.4	5928.7	5985.1	32.3	45.9	1481.1	0	33.1	15.1	48.2	68.0	1624.9
FILT	14.1	1015.4	1029.4	33.9	17.9	606.1	0	0	0	0	0	0
SWSEP	44.3	2965.0	3009.3	33.4	59.7	1994.0	0	0	0	0	0	0
SIEV	40.5	6913.0	6953.5	32.9	119.4	3929.2	0	0	1.8	1.8	1.0	60.2
Total	2511.1	16,822.1	19,333.1	160.8	242.9	8010.4	20.8	33.1	16.9	70.8	69.0	2273.7

5.5 Summary

A novel MFCA-based approach is presented in this chapter for prioritisation of waste recovery. This approach considers the hidden costs allocated to process waste streams as a result of prior processing steps. A sago case study is solved to illustrate the proposed approach. The trends of prioritisation of waste recovery are also analysed. It is noted that there are several factors, such as HUC, CFC, discharged waste's quality and amount, will affect the prioritisation of waste recovery. To determine minimum THC of discharged waste, these factors are traded-off via developed MFCA-based approach. Hence, this approach can be adopted as selection tool to aid decision maker in selection of waste stream to be recovered so that economic and environmental performance of manufacturing processing can be improved.

In this chapter, prioritisation of waste recovery is performed merely based on the cost associated with waste streams which can be determined by MFCA-based prioritisation approach. This approach is further extended in next chapter for prioritisation of resources recovery considering the costs, quality and quantity of waste streams simultaneously.

CHAPTER 6

INTEGRATED DESIGN OF TOTAL RESOURCE CONSERVATION NETWORKS AND INDUSTRIAL PROCESSES VIA MATERIAL FLOW COST ACCOUNTING

6.1 Introduction

Numerous process integration approaches were developed for synthesis and optimisation of resource conservation networks (RCNs). However, most of the recovery strategy used in the previous developed approaches is mainly based on quality and quantity of waste streams. In case where the quality of waste streams is same, the previous developed approaches are unable to prioritise the waste streams to be recovered. Based on the concept of Material Flow Cost Accounting (MFCA), the cost associated in the waste streams to be recovered can be determined. As presented in Chapter 5, based on the associated cost of waste streams, prioritisation of waste streams for recovery can be performed. However, in case where the costs, quality and quantity of waste streams are considered simultaneously for prioritisation of waste recovery, different recovery strategy might be found. It is noted that different recovery strategy leads to different economic performance of industrial processes. Therefore, in this chapter, MFCA-based prioritisation approach developed in Chapter 5 is further extended as extended MFCA (eMFCA)-based prioritisation approach. This proposed approach considers simultaneously the costs of an industrial, quantity and quality of waste streams for material recovery. In addition, this proposed approach able to synthesise an optimum total RCN and industrial processes simultaneously. To illustrate the proposed approach, a sago industrial case study is solved in this chapter.

6.2 Material Flow Cost Accounting (MFCA)-based Prioritisation Approach

MFCA-based prioritisation approach presented in Chapter 5 is used to prioritise the recovery of waste streams based on MFCA concept (Kokubu and Tachikaw, 2013). According to Kokubu and Tachikawa (2013), all waste streams can be quantified in monetary units based on the total processing cost (material, energy and system costs) and the material distribution percentages. Figure 2.1 in Chapter 2 shows distribution of cost into product and waste streams based on MFCA concept.

As shown in Figure 2.1, the total processing cost of USD 950,000 (= USD 650,000 + USD 50,000 + USD 250,000) can be distributed based on the material distribution percentages of output (70%) and waste (30%) streams. In order to determine the total waste cost, the waste management cost (USD 50,000) is then added up as USD 270,000. Comparing with the conventional approach, the material, energy and management costs are only considered in the production of output instead of distributed to the waste streams. Based on MFCA approach, an actual total cost which used to generate waste can be determined.

Viewing the benefits and advantageous of MFCA, the MFCA concept is extended in Chapter 5 by introduced Carry–Forward Cost (CFC) and Hidden Cost (HC) to prioritise waste recovery. As presented in Chapter 5, HC is a summation cost of CFC and processing cost (PC). Meanwhile, CFC is defined as a cost that is carried from its upstream or downstream processes to the respective process unit. To compare the differences between the concept of MFCA and the MFCA-based prioritisation approach, Figure 6.1 is given.

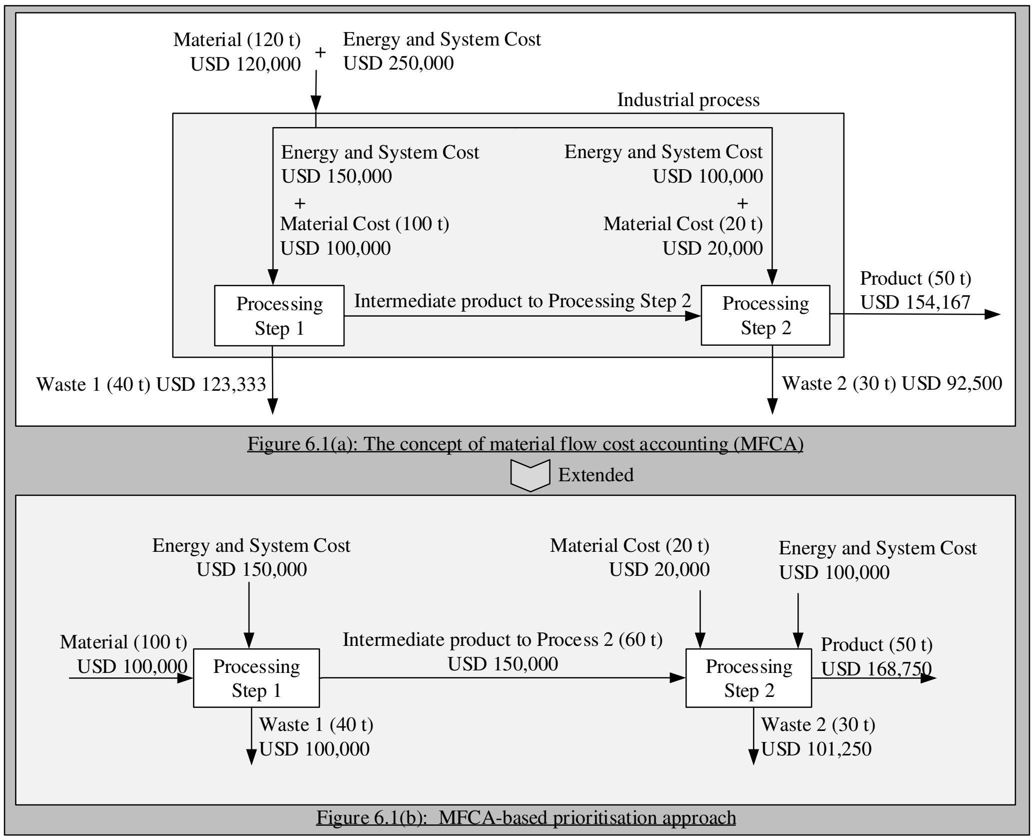

Figure 6.1: The concept of MFCA and MFCA-based prioritisation approach

Figure 6.1 (a) shows the concept of MFCA. As shown, an industrial process, which composed of Processing Step 1 and Step 2, required 120 tonnes of raw materials to produce 50 tonnes of product and 70 tonnes of wastes (40 tonnes of Waste 1 and 30 tonnes of Waste 2). Following with the concept of MFCA, a total processing cost of entire process (USD 120,000 + USD 250,000 = USD 370,000) is distributed to the product and wastes streams of the industrial process. In this case, the cost distributed to Product, Waste 1, and Waste 2 streams are determined as USD 154,167, USD 123,333, and USD 92,500, respectively.

In contrast, following with the MFCA-based prioritisation approach, processing cost of each processing step is considered instead to determine the overall cost distributed to product and waste streams. To illustrate the approach, a same industrial process is shown in Figure 6.1 (b). As shown, Processing Step 1 required a total HC (PC + CFC) of USD 250,000 to produce 60 tonnes of intermediate product and 40 tonnes of Waste 1. Hence, based on the material distribution percentages, the cost distributed to intermediate product stream and Waste 1 stream is determined as USD 150,000 and USD 100,000 respectively. Note that, this distributed cost is also known as associated cost of streams in this thesis. In addition, in this case, no cost is carried to Processing Step 1 and hence CFC of Processing Step 1 is zero and only PC is considered. In Processing Step 2, a total HC of USD 270,000 is determined by summed up the PC (USD 20,000 + USD 100,000) and CFC (USD 150,000). Similarly, based on the material distribution percentages, a total associated cost of USD 168,750 and USD 101,250 is determined for product and Waste 2 streams. As shown, the cost associated with product and waste stream is different from those determined by the concept of MFCA. In other words, by considering the CFC and HC in MFCA-based prioritisation approach, significant impact is found on the cost associated with product and wastes streams. As mentioned in Chapter 5, HC reflects the cumulative effort invested through successive processing steps to generate the product and waste streams. Hence, HC is an important criterion for prioritisation of waste recovery. In Chapter 5, the waste streams to be recovered are prioritised based on the cost associated with waste streams and without considering the quality and quantity of waste streams. In case where the quality, quantity, and costs are considered simultaneously in prioritisation of waste recovery, recovery strategy might be different. It is noted that different recovery strategy will leads to different economic performance of an industrial process. In order to show the impact of recovery strategy on economic performance of an industrial process, the previous example is further analysed in Figure 6.2.

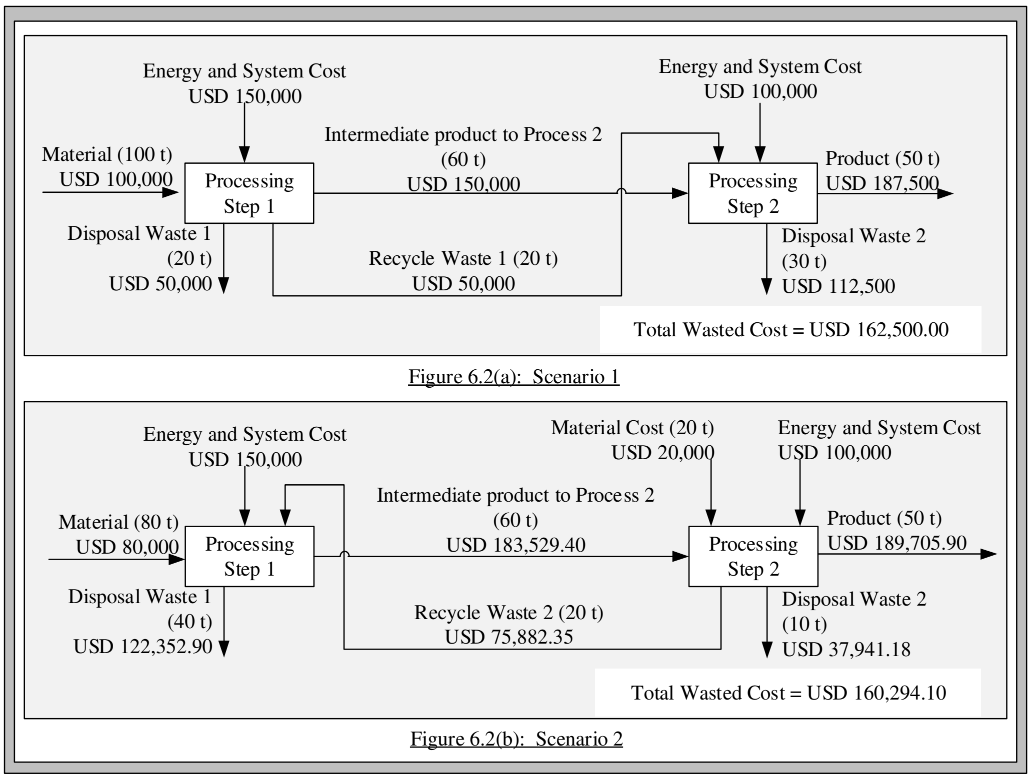

Figure 6.2: Recovery strategy with MFCA-based prioritisation approach

Figure 6.2 (a) shows the first scenario of recovery strategy where half of the waste from Processing Step 1 (20 tonnes) is recycled to Step 2 to reduce the consumption of fresh material. Based on the material distribution percentages, this waste stream is associated with a total cost of USD 50,000 and carried to Step 2. Hence, CFC increased from USD 150,000 to USD 200,000 and HC increased from USD 270,000 to USD 300,000 in Step 2 (see Figure 6.1 (b) and Figure 6.2 (a)). The increment of HC subsequently caused higher associated cost to product stream (USD 187,500) and waste stream (USD 112,500) of Step 2 compared to the case shown in Figure 6.1 (b) where no waste recovery is involved. As shown in Figure 6.2 (a), a total cost of USD 162,500 (USD 50,000 (Waste 1) + USD 112,500 (Waste 2)) is determined to be used for waste generation. This waste generation cost needs to be minimised as much as possible to increase economic performance of an industrial process.

Figure 6.2 (b) shows a different recovery strategy in an industrial process where 20 tonnes of waste materials from Processing Step 2 is recovered to Step 1 instead of from Step 1 to Step 2 as shown in Figure 6.2 (a). With this recovery strategy, HC of Processing Step 1 and 2 is different from Scenario 1. Based on the resulting HC, a new associated cost is determined for Waste 1 stream (USD 122,352.90) and Waste 2 stream (USD 37,941.18). In other words, a total USD 160,294.10 of cost is used to generate waste. This also means that the recovery strategy used in Figure 6.2 (b) gives a lower total cost to generate waste compared to the recovery strategy used in Figure 6.2 (a) with the same input of processing cost and raw material consumption. This demonstrated the fact that different recovery strategy will leads to different economic performance of an industrial process.

In order to overcome the limitations of work in Chapter 5 and the limitations of the previous network synthesis approaches, MFCA-based prioritisation approach is further extended to eMFCA-based prioritisation approach. The proposed approach considers costs of an industrial process, quality and quantity of waste streams simultaneously for resource recovery. In addition, the proposed approach able to synthesise an optimum RCN and industrial process simultaneously with a minimum total cost of waste generation. In order to demonstrate the proposed approach, a conceptual sago industrial case study is solved.

6.3 Problem Statement

The problem definition for simultaneous synthesis of a total RCN and an industrial process via eMFCA-based prioritisation approach is stated as follows: In generally, an industrial process composed of several processing steps, which defined as process *i* and process *i'*, where process *i* is not equal to process *i'* ($i \neq i'$), and process *i'* can be the upstream or downstream processes of process *i*. Basically, each process *i* requires $E_{i,e}$ of energy $e \in E$, $M_{i,m'}$ of raw material $m' \in M'$, and $K_{i,k}$ of intermediate material $k \in K$ to produce product P_i and $W_{i,w}$ of waste $w \in W$ (by-products). Such waste *w* can be classified into direct reused/recycled waste $q \in Q$ and waste $y' \in Y'$ to be disposed to the environment. This goes same to process *i'* as shown in Figure 5.1 (Chapter 5).

In order to reduce environmental issues, waste to be disposed is vital to be treated in a waste treatment plant. After the waste treatment, the treated waste can be reused/recycled to process *i* or process *i'* to reduce the waste generation and to increase economic performance of an industrial process. Therefore, a total RCN as shown in Figure 6.3 is vital to be formed for an industrial process.

As shown, a set of process source, $h \in H$ possessing processing cost (PC) of $Cost_h^{PC}$, generate a fixed flowrate of waste, F_h with fixed concentration of contaminant *b*,

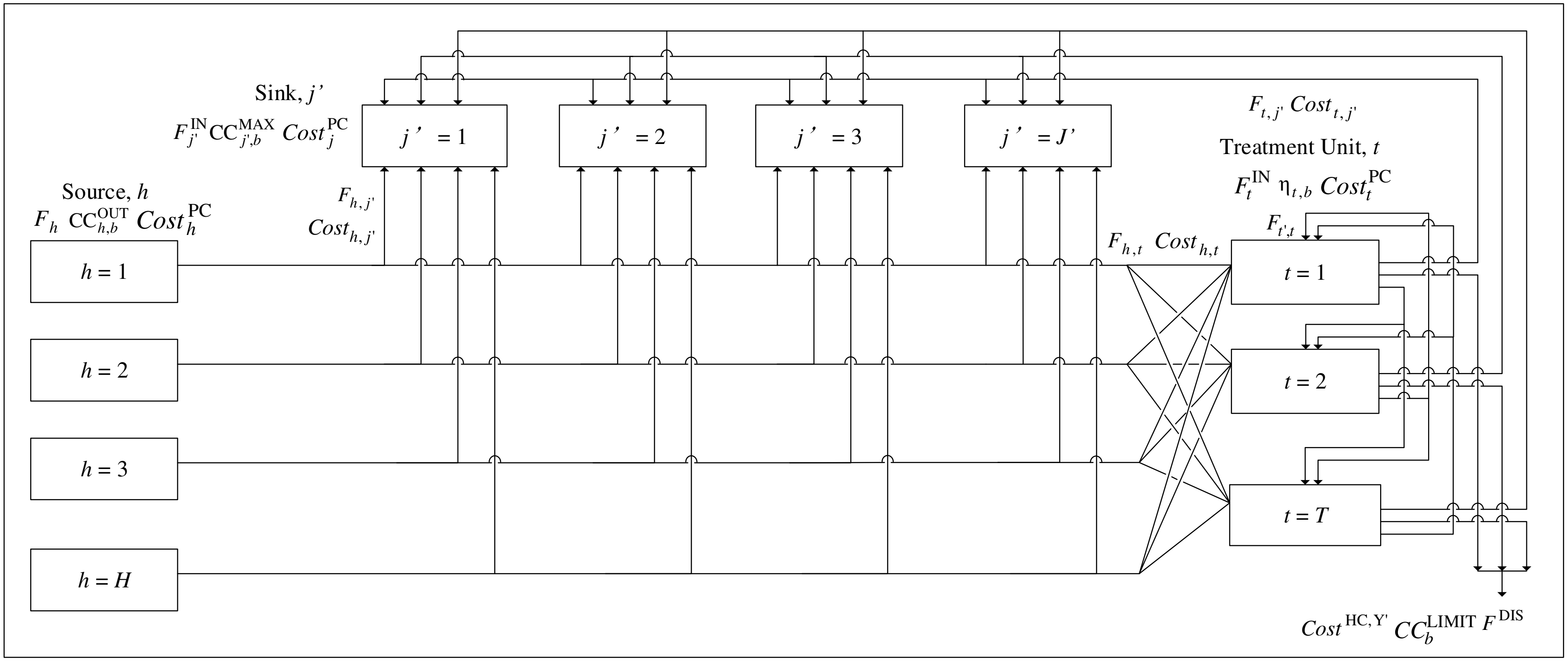

Figure 6.3: A generic superstructure of resource conservation network (RCN)

$CC_{h,b}^{OUT}$. The waste is either sent to treatment unit *t* with flowrate $F_{h,t}$ or direct reused/recycled to a set of process sink $j' \in J'$ with flowrate $F_{h,j'}$, as shown in Figure 6.3. The CFC of process source *h* to treatment unit *t* and process sink *j'*, are denoted as $Cost_{h,t}$ and $Cost_{h,j'}$ respectively. Each treatment unit $t \in T$ with total inlet flowrate of F_t^{IN} is given a fixed removal efficiency of $\eta_{t,b}$. Similarly, each treatment unit *t* possessing PC of $Cost_t^{PC}$. Note that part of the treated waste from treatment unit *t* can be reused/recycled to the process sink *j'* with flowrate of $F_{t,j'}$ and carry-forward cost (CFC) of $Cost_{t,j}$. The remaining treated waste can then be further treated in another treatment unit *t* with flowrate of $F_{t,t'}$ to meet discharge limit, CC_b^{LIMIT}. The total flowrate and carried cost of discharged waste are denoted as F^{DIS} and $Cost^{HC,Y'}$. A simplified superstructure that shows mass input-output of a treatment unit *t* is given in Figure 6.4.

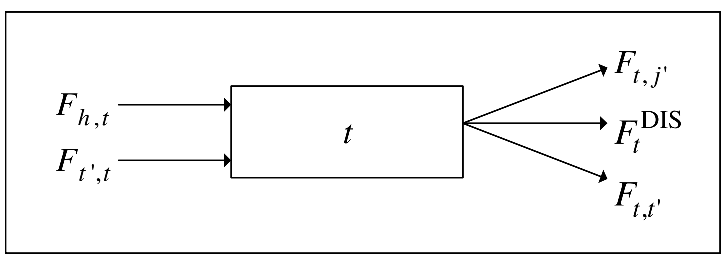

Figure 6.4: Mass input-output of a treatment unit t

On the other hand, total PC, inlet flowrate, and maximum inlet concentration are denoted as $Cost_{j'}^{PC}$, $F_{j'}^{IN}$ and $CC_{j',b}^{MAX}$ in each process sink *j'*. In order to incorporate the eMFCA-based prioritisation concept in simultaneous synthesising a total RCN and industrial processes, hidden cost (HC) of each discharged stream is determined. In order to reduce the waste generation cost, the optimisation objective is set as minimise total hidden cost (THC) of disposal waste, $Cost^{THC,Y'}$.

6.4 eMFCA-based Prioritisation Approach

In order to synthesise an optimum total RCN and industrial process simultaneously, a systematic approach is developed (Figure 6.5). As shown, related data on industrial processes such as process flow, mass balances, raw material and utility consumption, number of labour and all costs involved, etc. is first collected. Based on the utility consumption and its cost, total utility cost of industrial processes is determined. Next, based on the process description and process flow diagram, process sinks and process sources are identified. Note that, process sources are the processes that generate waste or by-product to be reused/recycled. Meanwhile, process sinks are defined as the potential processes that receive the waste generated from process sources. After the identification of process sinks and sources, characteristics of process sources needs to be determined for selection of waste treatment technologies. The treated waste can then be recovered to process sinks or treated to meet the discharge limit. In addition, process specifications of process sinks also needs to be determined in order to ensure the recovered waste meets the process sinks' requirement and does not disturb the current operation. Once the process sinks, process sources and the waste treatment technologies which can be used to improve the quality of the process sources are identified, a generic superstructure of total RCN can be developed as shown in Figure 6.3. Based on the developed superstructure, mathematical optimisation model (as discussed in detail in Section 6.5) are then developed for simultaneous synthesis and optimisation of total RCN and industrial processes. The developed model can be solved by any commercial optimisation software with different optimisation objectives.

Based on the optimisation results, an optimum total RCN and industrial processes can then be synthesised.

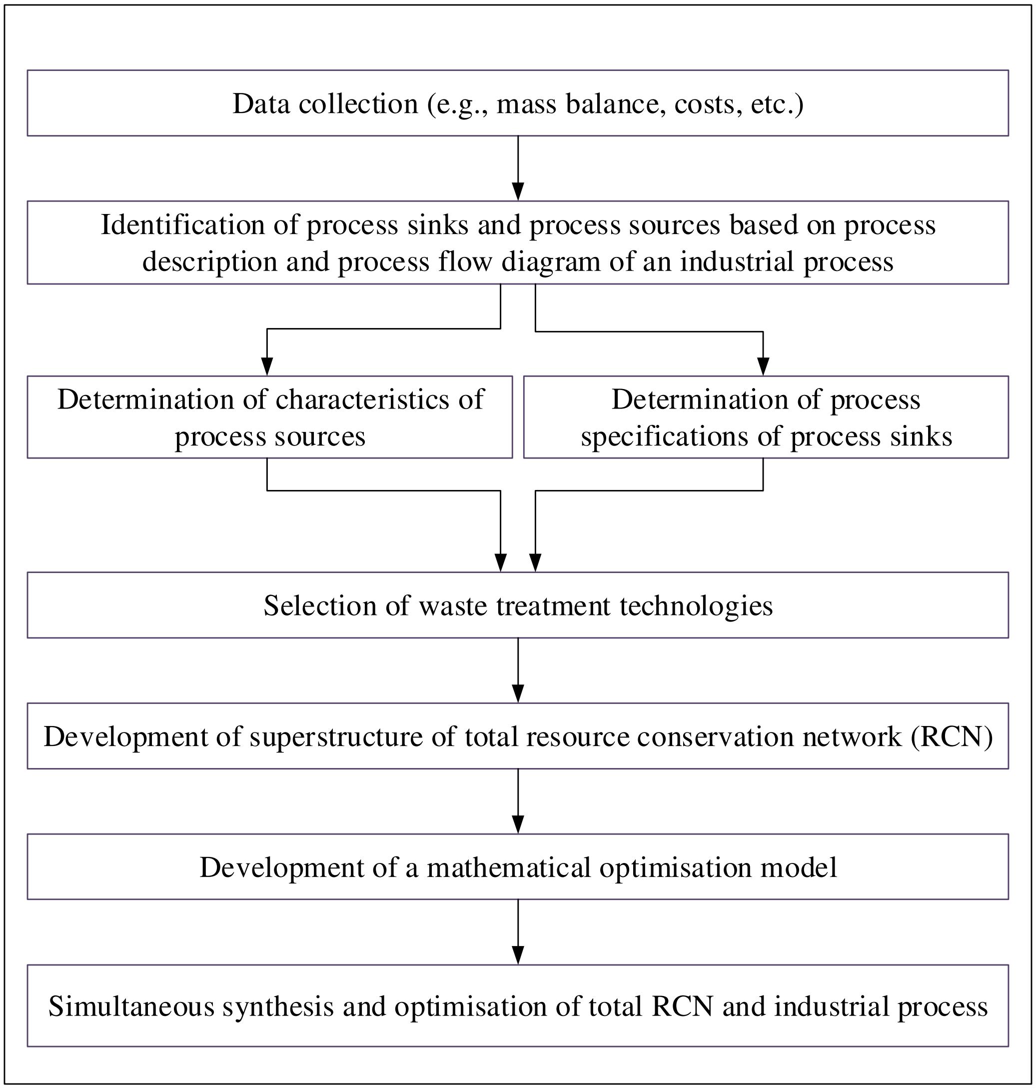

Figure 6.5: Procedure for simultaneous synthesis and optimisation of total RCN and industrial process via eMFCA-based prioritisation approach

6.5 Mathematical Formulations of eMFCA-based Prioritisation Approach

6.5.1 Mass Balances

As presented earlier in previous chapter, Figure 5.1, an industrial process is generally composed of a set of process $i \in I$ and process $i' \in I'$, where process i is not equal to process i' ($i \neq i'$) and process i' could be the upstream or downstream processes of process i. Besides, a set of desired product $p \in P$, intermediate material $k \in K$, and by-product or waste $w \in W$, are produced in each process i. Therefore, total output of process i, $\mathrm{T}_i^{\mathrm{OUT}}$ can be determined via Equation (6.1).

$$\mathrm{T}_i^{\mathrm{OUT}} = \sum_{i'}\sum_{k} \mathrm{K}_{i,i',k} + \sum_{p} \mathrm{P}_{i,p} + \sum_{w} \mathrm{W}_{i,w} \qquad \forall i \tag{6.1}$$

where $\mathrm{K}_{i,i',k}$ is the intermediate material k that transferred from process i to process i', while, $\mathrm{P}_{i,p}$ is the product p produced from process i, and $\mathrm{W}_{i,w}$ is the waste w generated from process i. Note that, the generated waste w is either direct reused/recycled to existing processes or disposed to the environment after a proper waste treatment, as shown in Equation (6.2).

$$\sum_{w} \mathrm{W}_{i,w} = \sum_{i'}\sum_{q} Q_{i,i',q} + \sum_{y'} Y'_{i,y'} \qquad \forall i \tag{6.2}$$

where $Q_{i,i',q}$ is the flow rate of direct reused/recycled waste q from process i to process i', while, $Y'_{i,y'}$ is the flow rate of disposal waste y' of process i that need to be transferred to a waste treatment plant. On the other hand, as mentioned previously, process *i'* are similar with process *i* which produced product *p*, intermediate material *k*, and waste *w*. Hence, Equations (6.1) and (6.2) can be re-wrote for process *i'* by substituted the index *i* with index *i'*.

Note that, process *i* and process *i'* can be identified as either process source *h* or process sink *j'* or both in total RCN. In case where the waste to be reused/recycled is generated from process *i* or *i'*, these processes will be identified as process source *h*. In contrast, in case where process *i* or *i'* accepted the reused/recycled wastes, the processes will be identified as process sink *j'* in total RCN as shown earlier in Figure 6.3.

As shown in Figure 6.3, a fixed flowrate of waste, F_h, is generated from process source *h*. This waste can be direct reused/recycled to process sink *j'* with flowrate of $F_{h,j'}$ or sent to treatment unit *t* with flowrate of $F_{h,t}$. Hence, the mass balance of the process source *h* and treatment unit *t* are given as:

$$\mathrm{F}_h = \sum_{j'} F_{h,j'} + \sum_t F_{h,t} \qquad \forall h \qquad (6.3)$$

$$F_t^{\mathrm{IN}} = \sum_h F_{h,t} + \sum_{t'} F_{t',t} \qquad \forall t \qquad (6.4)$$

where F_t^{IN} is the total inlet flowrate of treatment unit *t*, while, $F_{t',t}$ is the flowrate sent from the treatment unit *t'* (treatment unit other than treatment unit *t*) to treatment unit *t*. Since the flowrate of total inlet is always same as the total outlet, F_t^{OUT} , a constraint as shown in Equation (6.5) is added.

$$F_t^{\text{OUT}} = F_t^{\text{IN}} \qquad \forall t \qquad (6.5)$$

After the treatment process in treatment unit *t*, the treated waste can be either reused/recycled to process sink *j'* with flowrate of $F_{t,j'}$ or transferred to another treatment unit *t'* with flowrate of $F_{t,t'}$ for further treatment, or discharged to the environment with flowrate of F_t^{DIS} . Hence, total outlet of each treatment unit *t* can be determined via:

$$F_t^{\text{OUT}} = \sum_{j'} F_{t,j'} + \sum_{t'} F_{t,t'} + F_t^{\text{DIS}} \qquad \forall t \qquad (6.6)$$

For process sink *j'*, all the reused/recycled wastes that are transferred from process source *h* and treatment unit *t* are summed up to determine total inlet flowrate of process sink *j'* as given as:

$$F_{j'}^{\text{IN}} = \sum_{h} F_{h,j'} + \sum_{t} F_{t,j'} \qquad \forall j' \qquad (6.7)$$

6.5.2 Contaminant Balances

As mentioned in the problem statement, each process source *h* is given fixed concentration of contaminant *b* which is denoted as $\mathrm{CC}_{h,b}^{\mathrm{OUT}}$. Such process source *h* can be either direct reused/recycled to sink *j'* or transferred to treatment unit *t* for treatment. In treatment unit *t*, the process source *h* can be mixed with the treated source from other treatment unit (*t*') as shown in Figures 6.3 – 6.4. In order to determine the total inlet concentration of waste with contaminant *b* of each treatment unit *t*, $CC_{t,b}^{\mathrm{IN}}$, total mass load of contaminant *b* transferred from process source *h* and treatment unit *t'* to treatment unit *t* are first determined via equations below:

$$M_{h,b,t} = F_{h,t}\mathrm{CC}_{h,b}^{\mathrm{OUT}} \qquad \forall h \forall t \forall b \qquad (6.8)$$

$$M_{t',b,t} = F_{t',t}\mathrm{CC}_{t',b}^{\mathrm{OUT}} \qquad \forall t' \forall t \forall b \qquad (6.9)$$

where $M_{h,b,t}$ and $M_{t',b,t}$ are the mass load of contaminant *b* transferred from process source *h* to treatment unit *t*, and from treatment unit *t'* to treatment unit *t*. Meanwhile, $CC_{t',b}^{\mathrm{OUT}}$ is the concentration of contaminant *b* transferred from treatment unit *t'*. Then, total inlet concentration of contaminant *b* in each treatment unit *t*, $CC_{t,b}^{\mathrm{IN}}$, can be determined via Equation (6.10).

$$CC_{t,b}^{\mathrm{IN}} = \frac{\sum_{h} M_{h,b,t} + \sum_{t'} M_{t',b,t}}{F_t^{\mathrm{IN}}} \qquad \forall t \forall b \qquad (6.10)$$

In this thesis, it is assumed that treatment unit *t* has a fixed removal efficiency of contaminant *b*, $\eta_{t,b}$. Based on this removal efficiency, the outlet concentration of contaminant *b* in treatment unit *t*, $CC_{t,b}^{\mathrm{OUT}}$, can be determined via:

$$CC_{t,b}^{\mathrm{OUT}} = \frac{F_t^{\mathrm{IN}} CC_{t,b}^{\mathrm{IN}} \left[1 - \eta_{t,b}\right]}{F_t^{\mathrm{OUT}}} \qquad \forall t \forall b \qquad (6.11)$$

In order to comply with the discharged concentration limit, $\mathrm{CC}_b^{\mathrm{LIMIT}}$, the total outlet concentration of contaminant *b*, which can be determined via Equation (6.12), CC_b^{OUT}, must be lower than the limit, as shown in Equation (6.13).

$$CC_b^{\mathrm{OUT}} = \sum_t CC_{t,b}^{\mathrm{OUT}} \qquad \forall b \qquad (6.12)$$

$$CC_b^{\mathrm{OUT}} \leq \mathrm{CC}_b^{\mathrm{LIMIT}} \qquad \forall b \qquad (6.13)$$

Similarly to process sink *j'*, in order to determine the total inlet concentration of contaminant *b* of process sink *j'*, mass load of contaminant *b* transferred from process source *h* and treatment unit *t* to process sink *j'* are first determined via:

$$M_{h,b,j'} = F_{h,j'} \mathrm{CC}_{h,b}^{\mathrm{OUT}} \qquad \forall h \forall b \forall j' \qquad (6.14)$$

$$M_{t,b,j'} = F_{t,j'} \mathrm{CC}_{t,b}^{\mathrm{OUT}} \qquad \forall t \forall b \forall j' \qquad (6.15)$$

where $M_{h,b,j'}$ and $M_{t,b,j'}$ are the mass load of contaminant *b* transferred from process source *h* and treatment unit *t* to process sink *j'*. Then, total inlet concentration of contaminant *b* of process sink *j'*, $CC_{j',b}^{\mathrm{IN}}$, can be determined via:

$$CC_{j',b}^{\mathrm{IN}} = \frac{\sum_{h} M_{h,b,j'} + \sum_{t} M_{t,b,j'}}{F_{j'}^{\mathrm{IN}}} \qquad \forall j' \, \forall b \qquad (6.16)$$

In case there is limitation of inlet concentration of contaminant *b* in process sink *j'*, maximum limit of inlet concentration of contaminant *b*, $\mathrm{CC}_{j',b}^{\mathrm{MAX}}$ can be defined. In order to meet this process requirement, total inlet concentration of contaminant *b* of process sink *j'*, $CC_{j',b}^{\mathrm{IN}}$, must be lower than the maximum limit of inlet concentration of contaminant *b* as shown in Equation (6.17).

$$CC_{j',b}^{\mathrm{IN}} \le \mathrm{CC}_{j',b}^{\mathrm{MAX}} \qquad \forall j' \, \forall b \qquad (6.17)$$

6.5.3 Cost Evaluation

For industrial process, all costs involved in process *i* (i.e., material cost, energy cost, and system cost) are first collected from industrial management to determine the processing cost (PC) of process *i*, $Cost_{i}^{\mathrm{PC}}$, as shown as below:

$$\mathrm{Cost}_{i}^{\mathrm{PC}} = \mathrm{Cost}_{i}^{\mathrm{MAT}} + \mathrm{Cost}_{i}^{\mathrm{ENGY}} + \mathrm{Cost}_{i}^{\mathrm{SYM}} \qquad \forall i \qquad (6.18)$$

where $\text{Cost}_i^{\text{MAT}}$, $\text{Cost}_i^{\text{ENGY}}$, and $\text{Cost}_i^{\text{SYM}}$ are defined as material cost, energy cost, and system cost of process *i*. As reported in Chapter 5, hidden cost (HC) of process *i* can be determined via:

$$Cost_i^{\text{HC}} = Cost_i^{\text{PC}} + Cost_i^{\text{CFC}} \qquad \forall i \tag{6.19}$$

where $Cost_i^{\text{HC}}$ and $Cost_i^{\text{CFC}}$ are the HC and CFC of process *i*. Note that CFC was defined as a cost that is carried by direct reused/recycled waste *q* or intermediate material *k* to process *i*, and can be determined via:

$$Cost_i^{\text{CFC}} = \sum_{i'} \sum_{k} Cost_{i',i,k} + \sum_{i'} \sum_{q} Cost_{i',i,q} \qquad \forall i \tag{6.20}$$

where $Cost_{i',i,k}$ and $Cost_{i',i,q}$ are given as CFC that is carried by intermediate material *k* and direct reused/recycled waste *q* from process *i'* to process *i*. Since the direct reused/recycled waste *q* and intermediate material *k* are produced in process *i'*, both direct reused/recycled waste *q* and intermediate material *k* are carried part of the processing cost of process *i'*. Therefore, in order to determine the CFC that is carried by direct reused/recycled waste *q* and intermediate material *k*, the hidden unit cost (HUC) of process *i'* is first to be determined via:

$$Cost_{i'}^{\text{HUC}} = Cost_{i'}^{\text{HC}} / \text{T}_{i'}^{\text{OUT}} \qquad \forall i' \tag{6.21}$$

where $Cost_{i'}^{\text{HUC}}$, $Cost_{i'}^{\text{HC}}$, $\text{T}_{i'}^{\text{OUT}}$ are the HUC, HC, and total output of process *i'*. Then, the CFC that is carried by intermediate material *k*, $Cost_{i',i,k}$, and direct reused/recycled waste *q*, $Cost_{i',i,q}$, can be determined via:

$$\sum_{i'}\sum_{k} Cost_{i',i,k} = \sum_{i'}\sum_{k} Cost_{i'}^{\text{HUC}} \text{K}_{i',i,k} \qquad \forall i \tag{6.22}$$

$$\sum_{i'}\sum_{q} Cost_{i',i,q} = \sum_{i'}\sum_{q} Cost_{i'}^{\text{HUC}} \text{Q}_{i',i,q} \qquad \forall i \tag{6.23}$$

Based on the Equations (6.1) – (6.23), HC of process *i*, $Cost_{i}^{\text{HC}}$, can be determined. Then, HC of disposal waste *y*, $Cost_{i}^{\text{HC, Y'}}$ of process *i* can be determined via:

$$Cost_{i}^{\text{HC,Y'}} = \sum_{y'} \left[\frac{Cost_{i}^{\text{HC}}}{\text{T}_{i}^{\text{OUT}}} \right] Y'_{i,y'} \qquad \forall i \tag{6.24}$$

Note that, Equations (6.18) – (6.24) is applicable to process *i'* by substituted the index *i* with index *i'*.

For the total RCN as shown in Figure 6.3, HC of process source *h*, $Cost_{h}^{\text{HC}}$, process sink *j'*, $Cost_{j'}^{\text{HC}}$, and treatment unit *t*, $Cost_{t}^{\text{HC}}$ are determined via:

$$Cost_{h}^{\text{HC}} = Cost_{h}^{\text{PC}} + Cost_{h}^{\text{CFC}} \qquad \forall h \tag{6.25}$$

$$Cost_{j'}^{\mathrm{HC}} = Cost_{j'}^{\mathrm{PC}} + Cost_{j'}^{\mathrm{CFC}} \qquad \forall j' \qquad (6.26)$$

$$Cost_{t}^{\mathrm{HC}} = Cost_{t}^{\mathrm{PC}} + Cost_{t}^{\mathrm{CFC}} \qquad \forall t \qquad (6.27)$$

where $Cost_{h}^{\mathrm{PC}}$, $Cost_{j'}^{\mathrm{PC}}$, and $Cost_{t}^{\mathrm{PC}}$ are the PC of process source *h*, process sink *j'*, and treatment unit *t*; while, $Cost_{h}^{\mathrm{CFC}}$, $Cost_{j'}^{\mathrm{CFC}}$, and $Cost_{t}^{\mathrm{CFC}}$ are the CFC of process source *h*, process sink *j'*, and treatment unit *t*. As mentioned earlier, CFC is the cost carried by the intermediate material and reused/recycled waste. Therefore, CFC of process source *h*, process sink *j'*, and treatment unit *t* can be determined via:

$$Cost_{h}^{\mathrm{CFC}} = \sum_{i'} \sum_{k} Cost_{i',h,k} \qquad \forall h \qquad (6.28)$$

$$Cost_{j'}^{\mathrm{CFC}} = \sum_{i'} \sum_{k} Cost_{i',j',k} + \sum_{h} Cost_{h,j'} + \sum_{t} Cost_{t,j'} \qquad \forall j' \qquad (6.29)$$

$$Cost_{t}^{\mathrm{CFC}} = \sum_{t'} Cost_{t',t} + \sum_{h} Cost_{h,t} \qquad \forall t \qquad (6.30)$$

where $Cost_{i',h,k}$ is the CFC carried by the intermediate material *k* that transferred to process source *h* from its upstream or downstream process (process *i'*). Meanwhile, $Cost_{i',j',k}$ is defined as CFC carried by intermediate *k* that transferred to process sink *j'* from its upstream or downstream process (process *i'*); $Cost_{h,j'}$ and $Cost_{t,j'}$ are defined as CFC carried by the waste from process source *h* and treatment unit *t* to process sink *j'*. For the CFC of treatment unit *t*, $Cost_t^{\mathrm{CFC}}$, CFC carried by intermediate material (treated waste or regeneration waste) from treatment unit *t'* to treatment unit *t* is denoted as $Cost_{t',t}$, while, CFC carried by the waste from process source *h* to treatment unit *t* is denoted as $Cost_{h,t}$. In order to determine the CFC as abovementioned, HUC of process source *h*, $Cost_h^{\mathrm{HUC}}$, and HUC of treatment unit *t*, $Cost_t^{\mathrm{HUC}}$, are first to be determined via:

$$Cost_h^{\mathrm{HUC}} = Cost_h^{\mathrm{HC}} / \mathrm{T}_h^{\mathrm{OUT}} \qquad \forall h \qquad (6.31)$$

$$Cost_t^{\mathrm{HUC}} = Cost_t^{\mathrm{HC}} / T_t^{\mathrm{OUT}} \qquad \forall t \qquad (6.32)$$

where $\mathrm{T}_h^{\mathrm{OUT}}$ and $\mathrm{T}_t^{\mathrm{OUT}}$ are the total outlet of process source *h* and treatment unit *t*. Then, CFCs as abovementioned can be determined via:

$$\sum_{i'} \sum_{k} Cost_{i',h,k} = \sum_{i'} \sum_{k} Cost_{i'}^{\mathrm{HUC}} \mathrm{K}_{i',h,k} \qquad \forall h \qquad (6.33)$$

$$\sum_{i'} \sum_{k} Cost_{i',j',k} = \sum_{i'} \sum_{k} Cost_{i'}^{\mathrm{HUC}} \mathrm{K}_{i',j',k} \qquad \forall j' \qquad (6.34)$$

$$\sum_{h} Cost_{h,j'} = \sum_{h} Cost_h^{\mathrm{HUC}} F_{h,j'} \qquad \forall j' \qquad (6.35)$$

$$\sum_{t} Cost_{t,j'} = \sum_{t} Cost_{t}^{\mathrm{HUC}} F_{t,j'} \qquad \forall j' \qquad (6.36)$$

$$\sum_{h} Cost_{h,t} = \sum_{h} Cost_{h}^{\mathrm{HUC}} F_{h,t} \qquad \forall t \qquad (6.37)$$

$$\sum_{t'} Cost_{t',t} = \sum_{t'} Cost_{t'}^{\mathrm{HUC}} F_{t',t} \qquad \forall t \qquad (6.38)$$

where $Cost_{i'}^{\mathrm{HUC}}$ is the HUC of process *i'* determined via Equation (6.21); $K_{i',h,k}$ and $K_{i',j',k}$ are the flowrate of intermediate material *k* that transferred from process *i'* to process source *h* and process sink *j'*. Meanwhile, $Cost_{t'}^{\mathrm{HUC}}$ is the HUC of treatment unit *t'*. Based on Equations (6.1) – (6.38), HC of process source *h*, process sink *j'*, and treatment unit *t* can be determined. Once the HC of treatment unit *t* is determined, HC of disposal waste *y'* of treatment unit *t*, $Cost_{t}^{\mathrm{HC,Y'}}$, can be determined via:

$$Cost_{t}^{\mathrm{HC,Y'}} = \sum_{y'} \left[\frac{Cost_{t}^{\mathrm{HC}}}{T_{t}^{\mathrm{OUT}}} \right] Y'_{t,y'} \qquad \forall t \qquad (6.39)$$

where T_{t}^{OUT} is the total output of treatment unit *t*, $Y'_{t,y'}$ is the disposal waste y' of treatment unit *t*. In order to determine total hidden cost (THC) of disposal waste, $Cost^{THC,Y'}$, Equation (6.40) is included in this model.

$$Cost^{\mathrm{THC,Y'}} = \sum_i Cost_i^{\mathrm{HC,Y'}} + \sum_t Cost_t^{\mathrm{HC,Y'}} + Cost^{MGT} \tag{6.40}$$

where $Cost^{MGT}$ is the waste management cost. Note that, the waste management cost is referred to the disposal cost which is charged by licensed agents to handle the untreatable disposal waste generated from treatment unit t (e.g., carbon, sludge, etc.). In order to synthesise an optimum total RCN and industrial processes simultaneously with maximum economic performance and minimum total disposal cost which also known as total waste generation cost ($Cost^{\mathrm{THC,Y'}}$), the optimisation objective is set as Equation (6.41).

Minimise $Cost^{\mathrm{THC,Y'}}$ (6.41)

Note that this model is a non-linear program (NLP) and can be solved by any commercial optimisation software. In order to demonstrate the proposed approach, the case study used in Chapter 5 is resolved in next section.

6.6 Case Study

In order to suit the work of this chapter, the block diagram used in Chapter 5 (Figure 5.2) has been revised to Figure 6.6 in this chapter. Figure 6.6 shows the process flow diagram of sago starch extraction process (SSEP).

As shown, during the production of sago starch, sago barks are generated during the debarking process; while sago fibres are generated from fibre separation (FSEP) and sieving (SIEV); and sago wastewater is generated from FSEP, SIEV, starch water separation (SWSEP), and filtration (FILT). In addition, huge amount of river water (342 m^3) is required for sago starch production. Such water is pumped to the existing water treatment process (WTP) for treatment and then supplied 36 m^3, 87 m^3, and 120 m^3 to rasping (RPG), FSEP and SIEV respectively. Meanwhile, FSEP, SIEV, SWSEP, and FILT generated 79 m^3, 119.4 m^3, 59.7 m^3, and 17.9 m^3 of wastewater, respectively, during sago starch production. In order to reduce the usage of river water and the generation of wastewater, part of the generated wastewater from FSEP, SIEV, SWSEP, and FILT can be direct reused/recycled to RPG, FSEP, and SIEV processes. The remaining wastewater is then transferred to wastewater treatment plant (WWTP) for treatment so that the treated water is complied with the discharge limit before being discharged to the environment (see Figure 6.7). Via the recovery strategy, the environmental issue also can be minimised. In addition, the treated water (regeneration water) can be reused/recycled to RPG, FSEP, and SIEV processes to further reduce the usage of river water and the generation of wastewater as shown in Figure 6.7. Based on the mass flowrate as shown in Figure 6.6, total amount of desired products produced, intermediate products produced, and waste generated in each process of SSEP as well as the total output of each process can be determined as summarised in Table 6.1. Besides, based on the input given by industrial partner, the quality of wastewater generated from FSEP, SIEV, SWSEP, and FILT processes and the quality of the treated water from WTP can be deduced as shown in Table 6.2. Apart from this, the maximum inlet water quality of RPG, FSEP, and SIEV processes, which is estimated based on the input of industrial partner as well as the quality limit of discharged water (Legal Research Board, 2010) are also shown in Table 6.2.

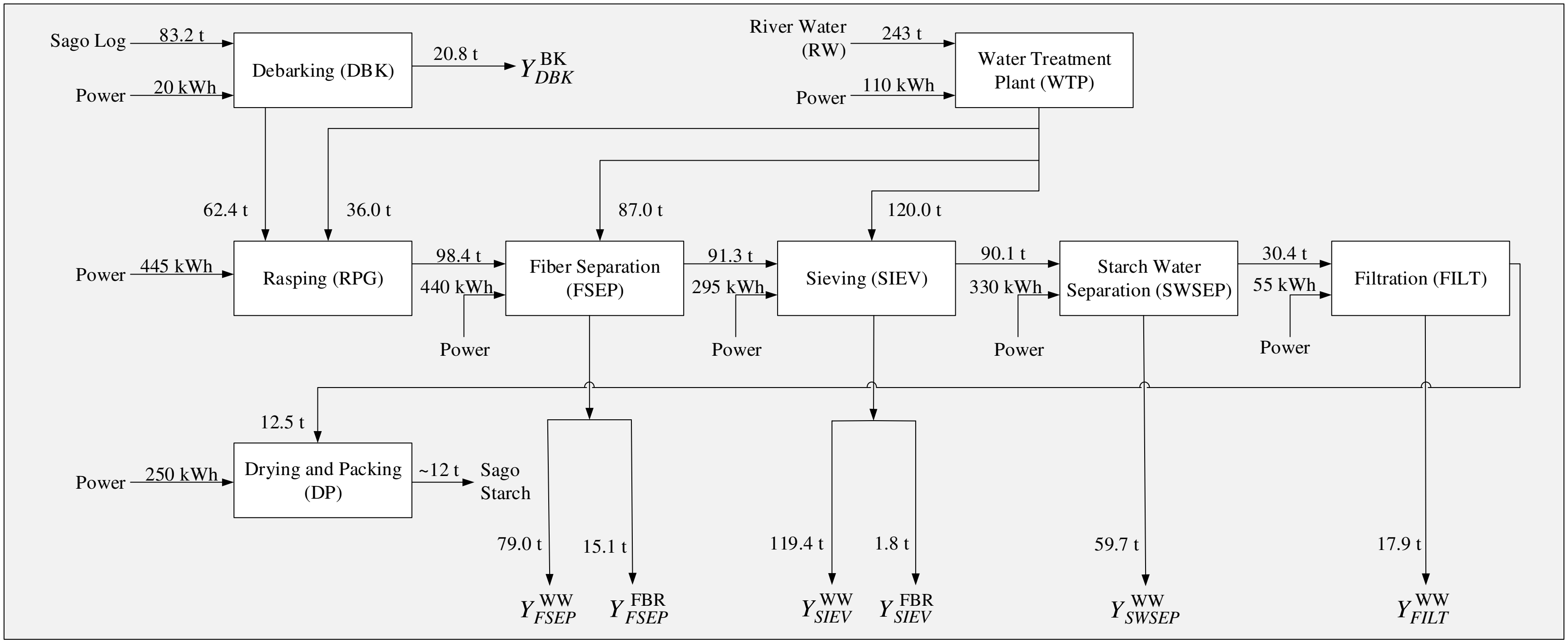

Figure 6.6: Process flow diagram of sago starch extraction process (SSEP)

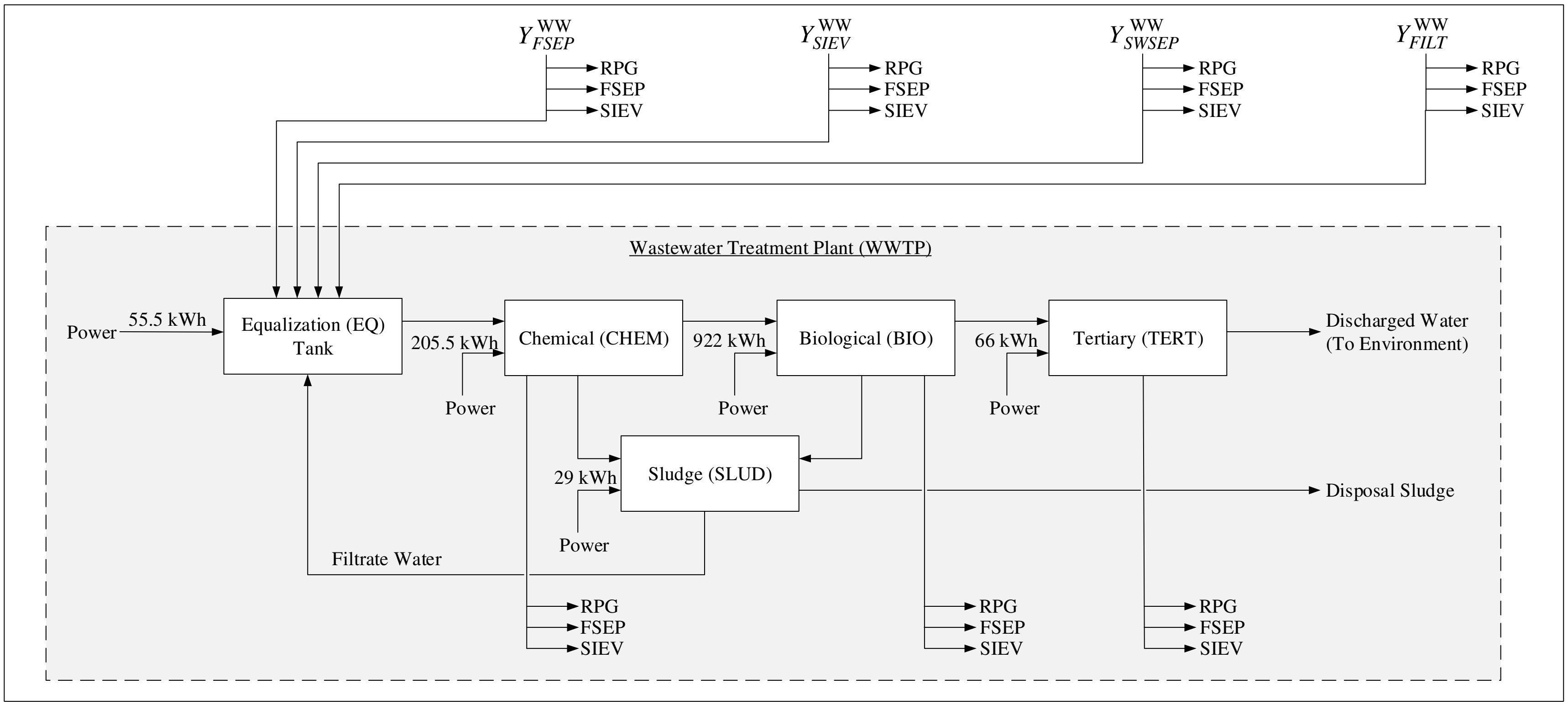

Figure 6.7: Process flow diagram of wastewater treatment plant (WWTP)

Table 6.1: Mass flowrate of desired products, intermediate products, wastes and total output of each sago starch extraction process

Processes	Desired Product, P_i (t)	Wastes, W_i (t)			Intermediate Product, $\sum_{i'} K_{i,i'}$ (t)	Total Output, T_i^{out} (t)
		Bark	Wastewater	Fibre		
WTP	0	0	0	0	$\sum_{j'} F_{WTP,j'}$	$\sum_{j'} F_{WTP,j'}$
DBK	0	20.8	0	0	62.4	83.2
RPG	0	0	0	0	98.4	98.4
FSEP	0	0	79.0	15.1	91.3	185.4
SIEV	0	0	119.4	1.8	90.1	211.3
SWSEP	0	0	59.7	0	30.4	90.1
FILT	0	0	17.9	0	12.5	30.4
DP	12.0	0	0	0	0	12.0

Table 6.2: Quality of wastewater and treated water and maximum of inlet and discharged water quality

	Water Quality, $CC_{h,b}^{OUT}$ (ppm)				
	COD	BOD	N	TDS	TSS
Wastewater:					
FSEP	11,650	5,750	110	8,250	4,800
SIEV	4,630	2,280	45	3,270	1,900
SWSEP	8,410	2,530	45	3,270	9,520
FILT	9,350	2,800	50	3,640	10,580
Treated Water:					
RW	150	100	10	100	100
	Maximum Quality of Inlet Water, $CC_{j',b}^{MAX}$ and Discharged Limit, CC_{b}^{LIMIT} (ppm)				
	COD	BOD	N	TDS	TSS
Inlet water:					
RPG	300	150	20	150	150
FSEP	300	150	20	150	150
SIEV	300	150	20	150	150
Discharged Water	200	50	20	100	100

As abovementioned, all the remaining wastewater is transferred to WWTP. In this case, WWTP is consists of an equalisation (EQ) tank, chemical, biological, and tertiary treatment processes. The wastewater is first transferred to EQ tank for mixing before chemical, biological, and tertiary treatment. Note that, sludge is generated from chemical and biological treatment processes. Hence, sludge treatment unit is included in WWTP. Therefore, Equation (6.6) is revised as below:

$$F_t^{OUT} = \sum_{j'} F_{t,j'} + \sum_{t'} F_{t,t'} + F_t^{DIS} + F_t^{SLUD} \qquad \forall t \qquad (6.42)$$

where F_t^{SLUD} is the flowrate of sludge generated in treatment unit *t*.

In order to determine total flowrate of sludge sent to sludge treatment unit, F^{SLUD}, Equation (6.43) is given as:

$$F^{\mathrm{SLUD}} = \sum_t F_t^{\mathrm{SLUD}} \qquad \forall t \tag{6.43}$$

Note that, sludge is generated based on the given contaminant removal efficiency, sludge generation yield, concentration of sludge generation, and required chemical dosage as shown in Table 6.3, and can be determined via:

$$F_t^{\mathrm{SLUD}} = \frac{\sum_b F_t^{\mathrm{IN}} CC_{t,b}^{\mathrm{IN}} \eta_{t,b} \mathrm{S}_{t,b}^{\mathrm{SLUD}} + \sum_c F_t^{\mathrm{IN}} \mathrm{DOSE}_{t,c} \mathrm{S}_c^{\mathrm{SLUD}}}{\mathrm{CC}_t^{\mathrm{SLUD}}} \qquad \forall t \tag{6.44}$$

where $\mathrm{S}_{t,b}^{\mathrm{SLUD}}$ is the sludge generation yield in each treatment unit *t* caused by removal of contaminant *b*. Meanwhile, $\mathrm{S}_c^{\mathrm{SLUD}}$ is the sludge generation yield due to the usage of chemical *c*; $\mathrm{DOSE}_{t,c}$ is the dosage of chemical *c* required in treatment unit *t*; and $\mathrm{CC}_t^{\mathrm{SLUD}}$ is the concentration of sludge generated in treatment unit *t*.

For the disposal sludge, the amount, $F_{\mathrm{DIS}}^{\mathrm{SLUD}}$, can be determined via:

$$F_{\mathrm{DIS}}^{\mathrm{SLUD}} = \sum_t F_t^{SLUD} \mathrm{CC}_t^{\mathrm{SLUD}} \Big/ \mathrm{DRY}_{\mathrm{DIS}}^{\mathrm{SLUD}} \tag{6.45}$$

where $\mathrm{DRY}_{\mathrm{DIS}}^{\mathrm{SLUD}}$ is the expected dryness of sludge after the sludge treatment process. In this case, the expected sludge dryness is given as 25%.

Table 6.3: Removal efficiency, yield and concentration of sludge generation, and required chemical dosage in wastewater treatment plant

	Removal Efficiency, $\eta_{t,b}$ (%)				
	COD	BOD	N	TDS	TSS
CHEM	65	60	10	98	98
BIO	95	95	80	35	35
TERT	60	60	0	10	10
	Sludge Generation yield, $S_{t,b}^{SLUD}$				
	COD	BOD	N	TDS	TSS
CHEM	0	0	0	1	1
BIO	0.35	0	0	1	0
TERT	0	0	0	0	0
	Concentration of Sludge Generation, CC_t^{SLUD} (kgSS/m^3)	Required Chemical Dosage, $DOSE_{t,c}$ (ppm)			
		Coagulant	Polymer	NaOH	
CHEM	50	500	5	300	
BIO	8	0	0	0	
TERT	0	0	0	0	

As a normal practice in Malaysia, after the sludge treatment, the sludge is disposed via a licensed agent either to landfill or "Kualiti Alam" (a hazardous waste management centre in Malaysia) for final disposal. Meanwhile, filtrate water generated from sludge treatment unit can be determined via:

$$F_{FILTRATE}^{SLUD} = F^{SLUD} - F_{DIS}^{SLUD} \quad (6.46)$$

Note that, this filtrate water is then returned to the EQ tank and go through the treatment processes again in WWTP. In this case, the concentration of the filtrate water is given as 2,460 ppm of chemical oxygen demand (COD), 1,220 ppm of biochemical oxygen demand (BOD), 60 ppm of ammonical-nitrogen (NH_3-N), 130 ppm of total dissolved solid (TDS), and 130 ppm of total suspended solid (TSS).

On the other hand, the regeneration water from chemical, biological and tertiary process can be recycled to RPG, FSEP, and SIEV processes to reduce the usage of treated water from WTP. However, the concentration sent to RPG, FSEP, and SIEV must be lower than the maximum limit as given in Table 6.2. The balance of the regeneration water is sent to next treatment unit for further treatment. At the end of the WWTP, the treated water is discharged from the tertiary process where the carbon is used as filtration material. The quality of discharged water must be complied with the discharged limit as given in Table 6.2. Hence, Equation (6.13) can be reformulated as:

$$CC_{TERT,b}^{\mathrm{OUT}} \leq \mathrm{CC}_{b}^{\mathrm{LIMIT}} \qquad \forall b \qquad (6.47)$$

Besides, in this case, total required amount of carbon, $\mathrm{CARBON}_{\mathrm{TERT}}$, can be determined via:

$$\mathrm{CARBON}_{\mathrm{TERT}} = F_{\mathrm{TERT}}^{\mathrm{IN}} \times \mathrm{CC}_{\mathrm{TERT,COD}}^{\mathrm{IN}} \times \eta_{\mathrm{TERT,COD}} \times \mathrm{CARBON}_{\mathrm{COD}}^{\mathrm{REQ}} \qquad (6.48)$$

where $F_{\mathrm{TERT}}^{\mathrm{IN}}$ is the total inlet flowrate of tertiary process; $\mathrm{CC}_{\mathrm{TERT,COD}}^{\mathrm{IN}}$ is the inlet concentration of COD of tertiary process; $\eta_{\mathrm{TERT,COD}}$ is the removal efficiency of COD in tertiary process; and $\mathrm{CARBON}_{\mathrm{COD}}^{\mathrm{REQ}}$ is the total carbon required per kg of COD removed.

Based on the process description of SSEP and WWTP, a generic superstructure of total water network is developed as shown in Figure 6.8. As shown, FSEP, SIEV, SWSEP, FILT are identified as process source *h* as they generated wastewater in SSEP that potential to be reused/recycled. Meanwhile, WTP process also identified as process source *h* in this case as it produced treated water that can be supplied to RSP, FSEP, and SIEV. Since RSP, FSEP, and SIEV are the processes that receive the reused/recycled wastewater from process sources *h* as well as the regeneration water from chemical (CHEM), biological (BIO), and tertiary (TERT) process, these processes are identified as process sink *j'* in this thesis.

In order to synthesise and optimise SSEP with WWTP and its total water network, PC of each process of SSEP and WWTP is first extracted and summarised as shown in Table 6.4.

Table 6.4: Processing cost (PC) of each processing step of sago starch extraction process (SSEP) and wastewater treatment plant (WWTP)

	Processing Cost (PC), USD/d
WTP	20.1
DBK	2,355.8
RPG	97.0
FSEP	56.4
SIEV	40.5
SWSEP	44.3
FILT	14.1
DP	51.5
EQ	6.1
CHEM	$26.6 + (0.538 \times F_{\mathrm{CHEM}}^{\mathrm{IN}})$
BIO	105.4
TERT	$11.26 + (0.0075 \times F_{\mathrm{TERT}}^{\mathrm{IN}} \times CC_{\mathrm{TERT,\ COD}}^{\mathrm{IN}})$
SLUD	$7.19 + (2.5 \times F_{\mathrm{CHEM}}^{\mathrm{SLUD}}) + (0.4 \times F_{\mathrm{BIO}}^{\mathrm{SLUD}})$

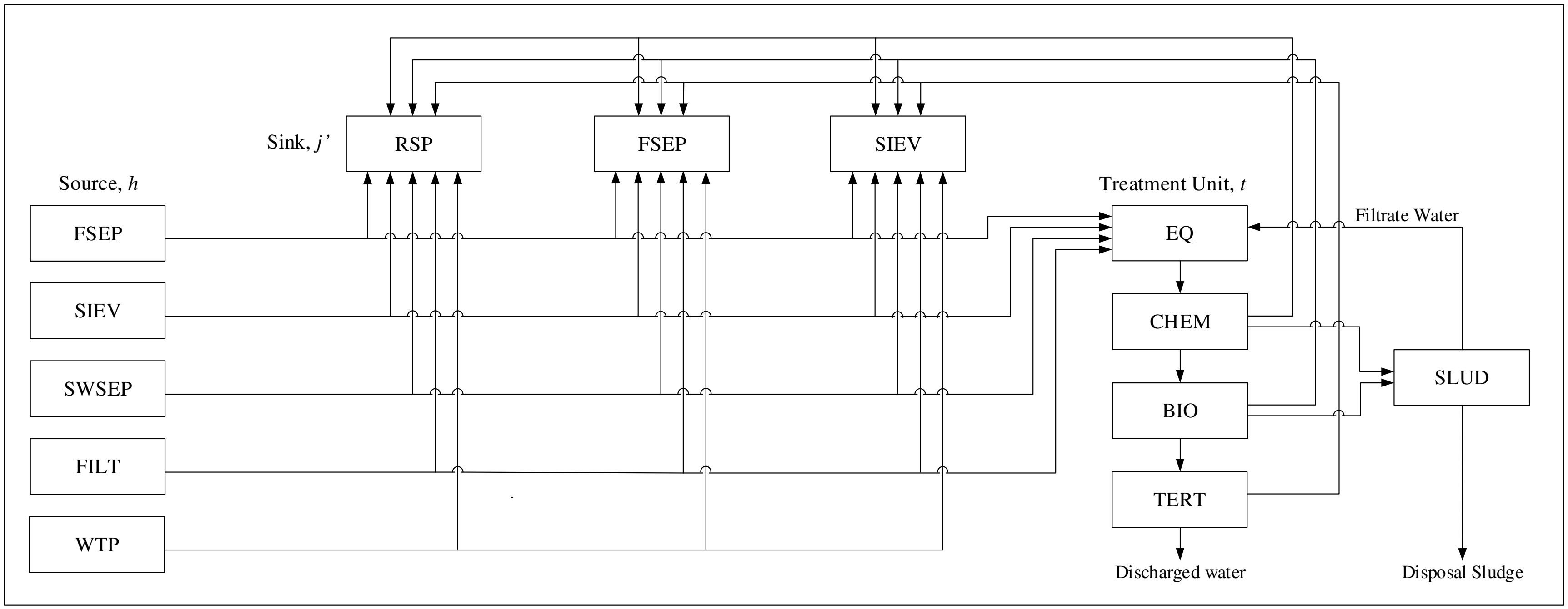

Figure 6.8: Generic superstructure of total water network for sago starch extraction process (SSEP)

Note that, PC of each process of SSEP is extracted from Chapter 5. Meanwhile, the PC of WWTP process is calculated based on the input of industry partner. As shown, the PC of CHEM, TERT, and SLUD treatment unit is highly depending on the inlet flowrate of respective treatment unit as well as the inlet concentration. Then, Equation (6.39) as discussed previously is re-wrote to generate Equations (6.49) – (6.50) to determine the hidden cost of disposal sludge, $Cost_{\text{SLUD}}^{\text{HC,Y'}}$, and discharged water, $Cost_{\text{TERT}}^{\text{HC,Y'}}$.

$$Cost_{\text{SLUD}}^{\text{HC,Y'}} = \left[\frac{Cost_{\text{SLUD}}^{\text{HC}}}{T_{\text{SLUD}}^{\text{OUT}}} \right] F^{\text{SLUD}} \tag{6.49}$$

$$Cost_{\text{TERT}}^{\text{HC,Y'}} = \left[\frac{Cost_{\text{TERT}}^{\text{HC}}}{T_{\text{TERT}}^{\text{OUT}}} \right] F_{DIS} \tag{6.50}$$

where $Cost_{\text{SLUD}}^{\text{HC}}$ and $Cost_{\text{TERT}}^{\text{HC}}$ are the HC of sludge and tertiary treatment unit. Meanwhile, $T_{\text{SLUD}}^{\text{OUT}}$ and $T_{\text{TERT}}^{\text{OUT}}$ are the total output of sludge and tertiary treatment unit. In addition, Equation (6.51) is given to determine the waste management cost, $Cost^{\text{MGT}}$:

$$Cost^{\text{MGT}} = [\text{CARBON}_{\text{TERT}} \times \text{KA}] + [F_{\text{DIS}}^{\text{SLUD}} \times \text{LAND}] \tag{6.51}$$

where KA and LAND are referred to the cost charged by Kualiti Alam and Landfill. In this case, KA is given as USD 1,166.7/t and LAND is given as USD 26.7/t.

In this model, there are a total of 179 of variables and 216 of constraints. Out of 89 of variables are nonlinear variables, and 101 of constraints are non-linear constraints. In addition, this model consists of numerous bilinear term equations. This caused the model become a non-linear programming (NLP) model. In order to ensure the global optimality, this model is solved via LINGO version 13 with global solver, a commercial optimisation software with a branch-and-bound based Global Optimisation Toolbox (Gau and Schrage, 2004), in an HP Compaq Elite 8300 with Intel® Core™ i5-3470 CPU (3.20GHz) and 4.00 GB RAM under a 32-bit operating system. The CPU time to obtain the global solution was approximately two minutes. By solving Equations (6.1) – (6.51) with the given data in Tables (6.1) – (6.4), an optimum SSEP with WWTP, and its optimum total water network are determined. Based on the optimised result, the minimum total disposal cost (waste generation cost) is located as USD 2,953/d. The PFD of the optimum SSEP with WWTP and the total water network are showed in Figures 6.9 and Figure 6.10.

As shown in Figures 6.9 and 6.10, a total of 342 m^3 of treated river water from WTP can be saved. This is due to a part of the wastewater and the regeneration water generated in SIEV, SWSEP, CHEM, and BIO processes is reused / recycled to RSP, FSEP, and SIEV process. Besides, a total of 21.42 t/d of treated water and 11.58 t/d of sludge are discharged to the environment as shown in Figure 6.9.

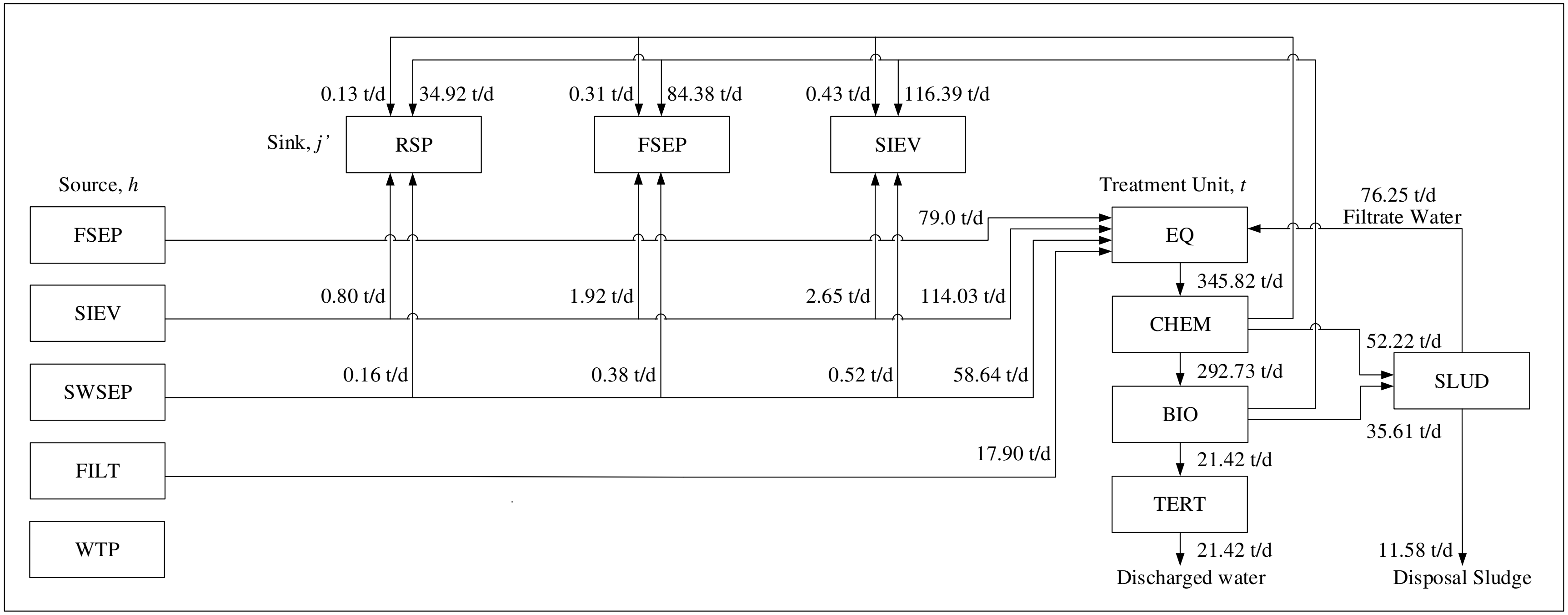

Figure 6.9: Optimum total water network of sago starch extraction process (SSEP)

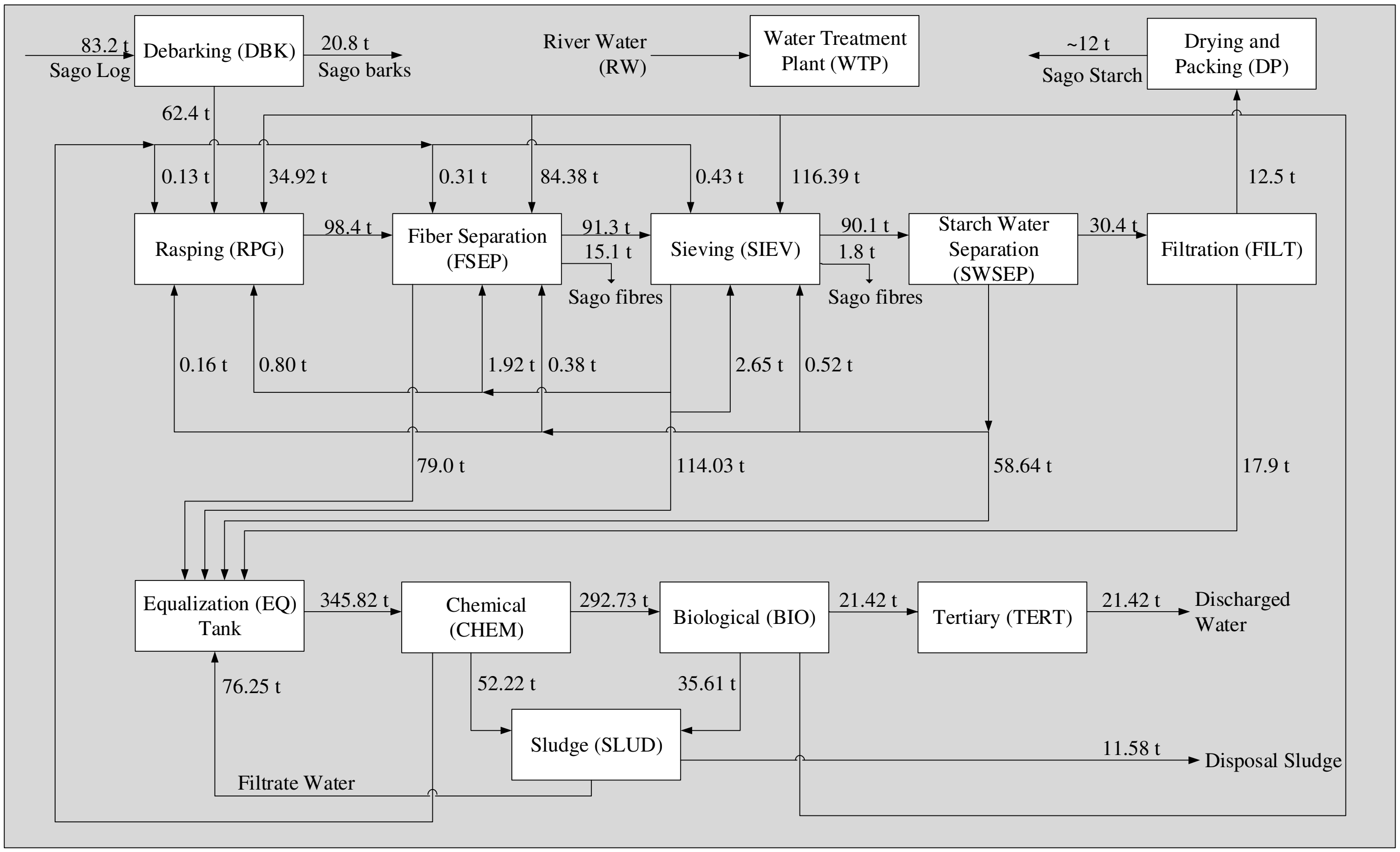

Figure 6.10: Optimum sago starch extraction process (SSEP) with wastewater treatment plant (WWTP)

6.7 Summary

In this thesis, the concept of material flow cost accounting (MFCA) is extended to develop eMFCA-based prioritisation approach for waste stream prioritisation. The proposed approach address the drawbacks of the previous developed network synthesis approaches as it able to prioritise the waste streams for recovery in the case where the quality and quantity of those waste streams are same. In addition, the proposed approach considers costs of industrial process, quality and quantity of waste stream to be recovered simultaneously for resources recovery. Furthermore, the proposed approach can synthesise and optimise industrial processes and total resource conservation network (RCN) simultaneously with a minimum total waste generation cost. This makes eMFCA-based prioritisation approach is a more appropriate approach to maximise the overall economic performance of industrial processes and its RCN compared to previous developed network synthesis approaches.

Apart from the sago wastewater recovery as presented in this chapter, recovery of sago barks and sago fibres are also presented in Chapters 7 and 8 of this thesis. The sago barks and fibres are converted into combined heat and power (CHP) and bioethanol to improve the sustainability of sago industry. In addition, techno-economic evaluation is also conducted to analyse the feasibility and viability of the conversion technologies in Malaysia context.

CHAPTER 7

TECHNO-ECONOMIC EVALUATIONS FOR FEASIBILITY OF SAGO-BASED BIOREFINERY, PART 1: ALTERNATIVE ENERGY SYSTEMS

7.1 Introduction

As mentioned in Chapters 1 and 2, serious environmental impacts are caused due to the huge amount of sago biomass generated and discharged to the environment from sago industry without proper treatment. In order to reduce such environmental pollutants and to increase economic performance of sago industry, recovery of sago biomass and sustainable conversion of sago biomass into value-added products is of paramount importance. However, sago-based biorefinery, which is a facility that converts sago biomass into value-added products via different conversion technologies, is yet to be implemented in sago industry. Therefore, a series of techno-economic evaluation is performed in this and next chapter (Chapter 8) to examine the feasibility of sago-based biorefinery. This is an essential and necessary initial step to encourage investors to invest in sago industry. In this chapter, techno-economic and environmental performance of sago-based combined heat and power (CHP) systems is analysed. In addition, a systematic techno-economic evaluation framework is also developed in this chapter. As an initial feasibility analysis of sago industry, three different conventional configurations of CHP system are adopted and analysed using the proposed evaluation framework. Different scenarios are proposed.

The proposed scenarios include a CHP system with on-site or off-site pre-treatment, hiring new labour (HL) or making use of current labour (UCL) of sago starch extraction process (SSEP) to operate the CHP systems. Such scenarios are presented to examine the importance of integration of SSEP and CHP system, and the importance of implementation of pre-treatment in CHP system. Via the scenarios, the impact of labour cost and feedstock cost on economic performance of a CHP system is analysed. Besides, the feasibility of such scenarios is also determined. The CHP system with the lowest payback period is then selected for sensitivity analysis. The sensitivity analysis is conducted due to variations in feedstock cost. In Chapter 8, the techno-economic evaluation is extended to examine the feasibility of integrated sago-based bioethanol production and energy systems. In both chapters (this chapter and Chapter 8), a sago starch processing facility from Sarawak, Malaysia with a starch production capacity of 12 t/d, as presented in Chapters 5 and 6, is used for techno-economic evaluations.

7.2 Problem Statement

This chapter is to analyse the feasibility and viability of sago biomass-based CHP system via a developed generic techno-economic evaluation framework. Sago biomass, such as, sago fibres and sago barks, is chosen as fuel sources for the CHP system. In addition, three conventional configurations of CHP system, as listed below, are selected for technical, environmental, and economic evaluation.

- Configuration 1: CHP system with normal pressure biomass boiler
- Configuration 2: CHP system with pressurised biomass boiler

- Configuration 3: CHP system with biomass gasification-based combined cycle

Based on the economic performance of CHP systems, the CHP system with the lowest payback period is determined. Sensitivity analysis is then performed on the determined system.

7.3 Generic Techno-economic Evaluation Framework

In order to evaluate technical, environmental, and economic performance of CHP systems with different sago biomass and configurations, a systematic generic evaluation framework is developed in this chapter, as shown in Figure 7.1. As shown, sago biomass to be used as feedstocks in CHP system is first determined. Next, literature review and market study are performed to identify the existing configurations of the CHP system using selected biomass as feedstock. In case where there is no existing configuration of the CHP system for the selected biomass, alternative configurations of the CHP system that are currently used for other biomass are then selected for consideration. In the event, the decision makers do not consider alternative configuration, the evaluation will end. Once the process configurations are decided, process modelling that involves theoretical calculation, excel spreadsheet based evaluation, and process flow sheet simulation, etc. are performed to determine the mass and energy balances of the system. Based on the results of process simulation, technical and environmental performance of the CHP system can be evaluated. Next, economic performance evaluation of the selected process configuration can be performed.

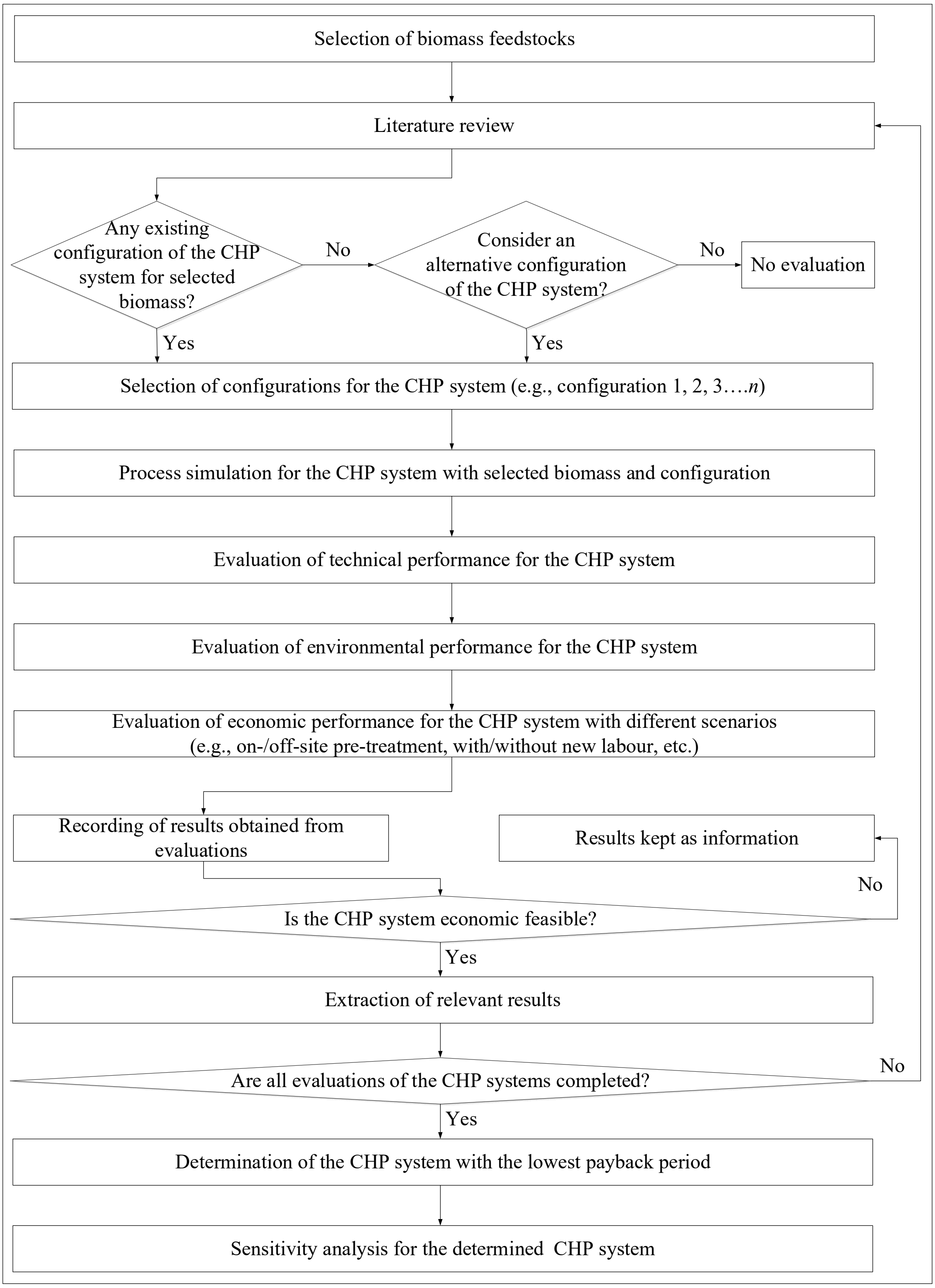

Figure 7.1: A systematic generic techno-economic evaluation framework for CHP systems

In this evaluation, economic feasibility of CHP system in different scenarios is further analysed. All the results obtained from techno-economic evaluation as well as environmental evaluation (e.g., total electricity generated, total carbon dioxide (CO_2) emissions reduced, payback period, etc.) are then compiled for further analysis. Note that these steps are repeated until evaluations of the various biomasses and configurations are completed. With the gathered information and analysis results, the CHP system with the lowest payback period is selected for sensitivity analysis. A detailed application of this proposed evaluation framework is demonstrated for sago biomass-based CHP systems as presented in the following sections.

7.4 Techno-economic Evaluation for Sago Biomass-based CHP Systems

7.4.1 Selection of Biomass Feedstocks and Configurations of CHP System

As mentioned in Chapter 2, sago biomass like sago barks and fibres are vital to be recovered and converted into heat and power. Hence, in this chapter, sago barks and fibres are selected as feedstocks for CHP systems. However, it is noted that there is no existing configuration of CHP system for those biomass. Therefore, based on the literature review, three alternative configurations of CHP system are selected in this chapter for techno-economic performance evaluation. The selected alternative configurations include CHP system with 1) normal pressure biomass boiler 2) pressurised biomass boiler, and 3) biomass-based gasifier. In this chapter, a small scale (12 t/d) sago starch processing facility as presented in Chapter 5 and Chapter 6 is used for performance evaluations. Based on this capacity of sago starch processing facility, approximately 20.8 tonne (wet basis) or 10.2 tonne (dry basis) of sago barks; and 16.9 tonne (wet basis) or 6.5 tonne (dry basis) of sago fibres are generated during sago starch processing. With these bases of sago barks and fibres as fuel sources in different CHP system configurations, technical, environmental, and economic performances are evaluated. The following sections discuss the selected configurations from the perspectives of operating conditions for industrial set-up, safety, and environmental and energy performances.

7.4.1.1 Configuration 1: CHP System with Normal Pressure Biomass Boiler

In this configuration, a normal pressure biomass boiler is used to generate steam. A normal pressure biomass boiler is the simplest form of conventional boilers, consisting of an economiser and a steam drum for generation of high pressure superheated steam by burning biomass. This is followed by steam expansion through back pressure and condensate steam turbines for power generation. The schematic diagram of this configuration is shown in Figure 7.2. The biomass is fed into the grate-fired boiler (Huang et al., 2013) with air for full combustion in the boiler. The resulting flue gas is released to the atmosphere and the ash is collected in ash grate to release from the bottom of the boiler. A flue gas temperature of >120^{o}C is maintained to allow the gas to flow through the chimney to be released at an acceptable height. Lower the exit temperature of the flue gas, higher is the heat recovery from the flue gas. Therefore, this limits the extent of heat recovery in the boiler. The boiler feed water (BFW), which is preheated in an economiser, is heated up in the boiler and then converted into saturated and ultimately into superheated high pressure steam (at 50 bar) in the steam drum of boiler. A part of the generated superheated steam is sent to the existing sago starch processing facility for drying purpose. Then, the remaining high pressure steam is expanded in a back pressure

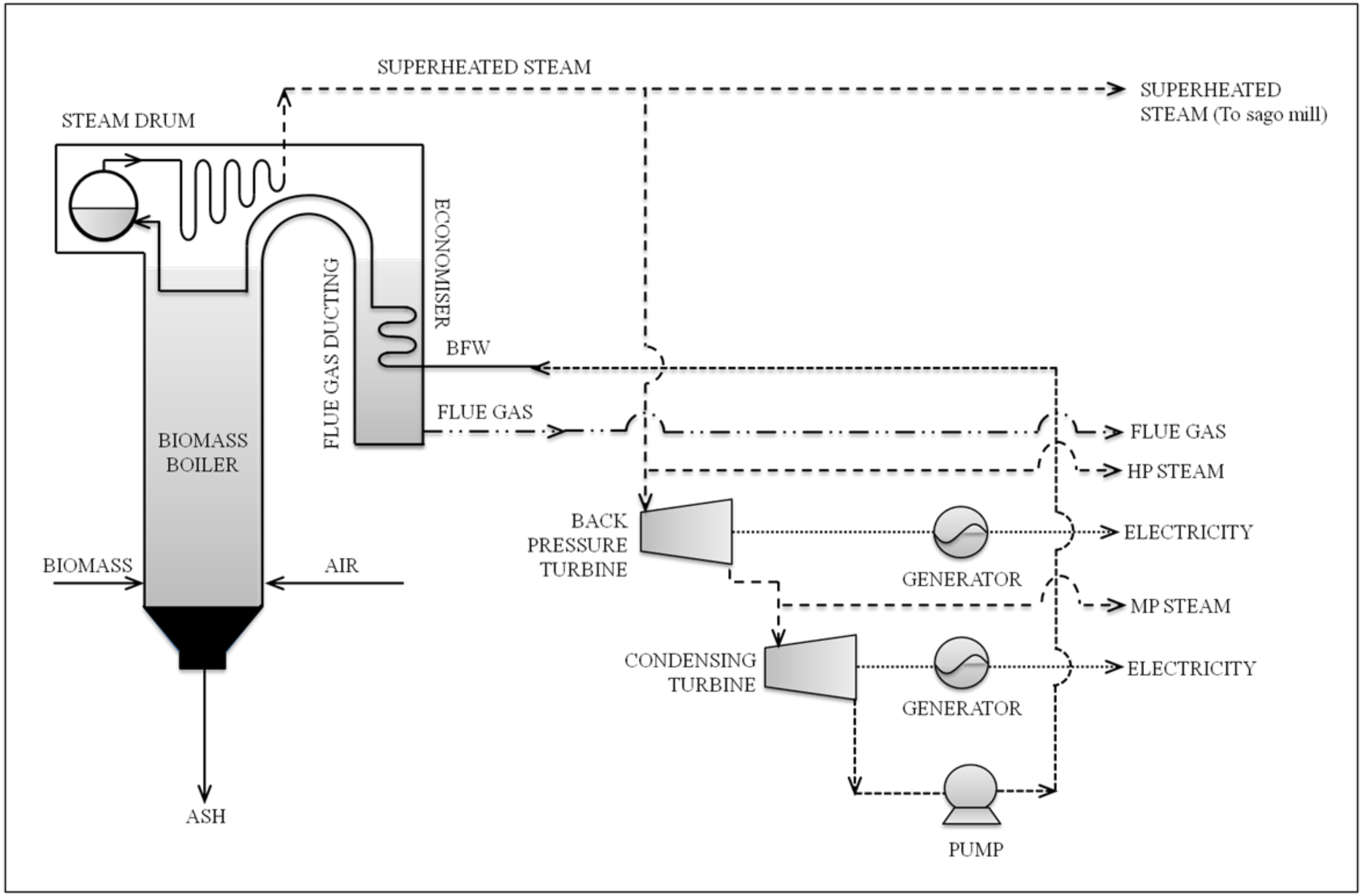

Figure 7.2: Schematic diagram of the biomass CHP system (Configuration 1)

steam turbine which is connected with a generator to generate electricity. The exit steam from the back pressure steam turbine is expanded in a condensate steam turbine and generator for more electricity generation. The generated condensate from the condensate turbine is recovered as BFW at ~1.0 bar and returned to the economiser via a pumping system. Via this system, the condensate is returned in a closed cycle after heat recovery through steam generation and transformation of heat into electricity generation via the steam. Since this configuration has much simpler design and requires less maintenance, the capital, operating and maintenance costs are relatively low compared to other configurations. However, the quality of the emitted gas from this configuration could be a problem as some particulates from ash may entrain with the flue gas. In most of the CHP systems, the usual pollutants are dust and particulates escaping from char and ash components of biomass and some volatile organic compounds such as phenolic compounds, known as tar. Through an activated carbon based gas filter at the exit, some of these pollutants can be removed from the flue gas emitted. A more intense clean-up may be necessary as discussed in Configuration 3.

7.4.1.2 Configuration 2: CHP System with Pressurised Biomass Boiler

A pressurised biomass boiler is used to generate pressurised moderate temperature exhaust gas for expansion through a gas expander connected with a generator to generate electricity, alongside the steam turbines as in Configuration 1. However, the pressurised biomass boiler needs to run with compressed air at the boiler pressure. The main parts of this CHP system are pressurised biomass boiler with economiser and steam generator attached to an air compressor, gas expander connected with a generator and back pressure and condensate steam turbines, as shown in Figure 7.3. The compressed air is supplied to the pressurised biomass boiler operating at a pressure of 30 bar to fully combust the biomass that is fed into the boiler through a feeding unit. Similar to Configuration 1, BFW economiser and steam generator are integral parts of the biomass boiler to generate high pressure steam. The resulting ash is collected in ash grate and removed from the bottom of the boiler. The flue gas at ~500^{o}C from the boiler is expanded to generate electricity through a generator. Then, the flue gas (120^{o}C as in Configuration 1) is released to the atmosphere. The flue gas quality remains as an issue, similar to Configuration 1. Meanwhile, some of the high pressure steam from biomass boiler is sent to existing sago starch processing facility for starch drying purpose and the remaining high pressure steam is expanded through back pressure and condensate steam turbines, respectively, to generate electricity. The condensate from the turbines is then pumped and returned as BFW to the economiser.

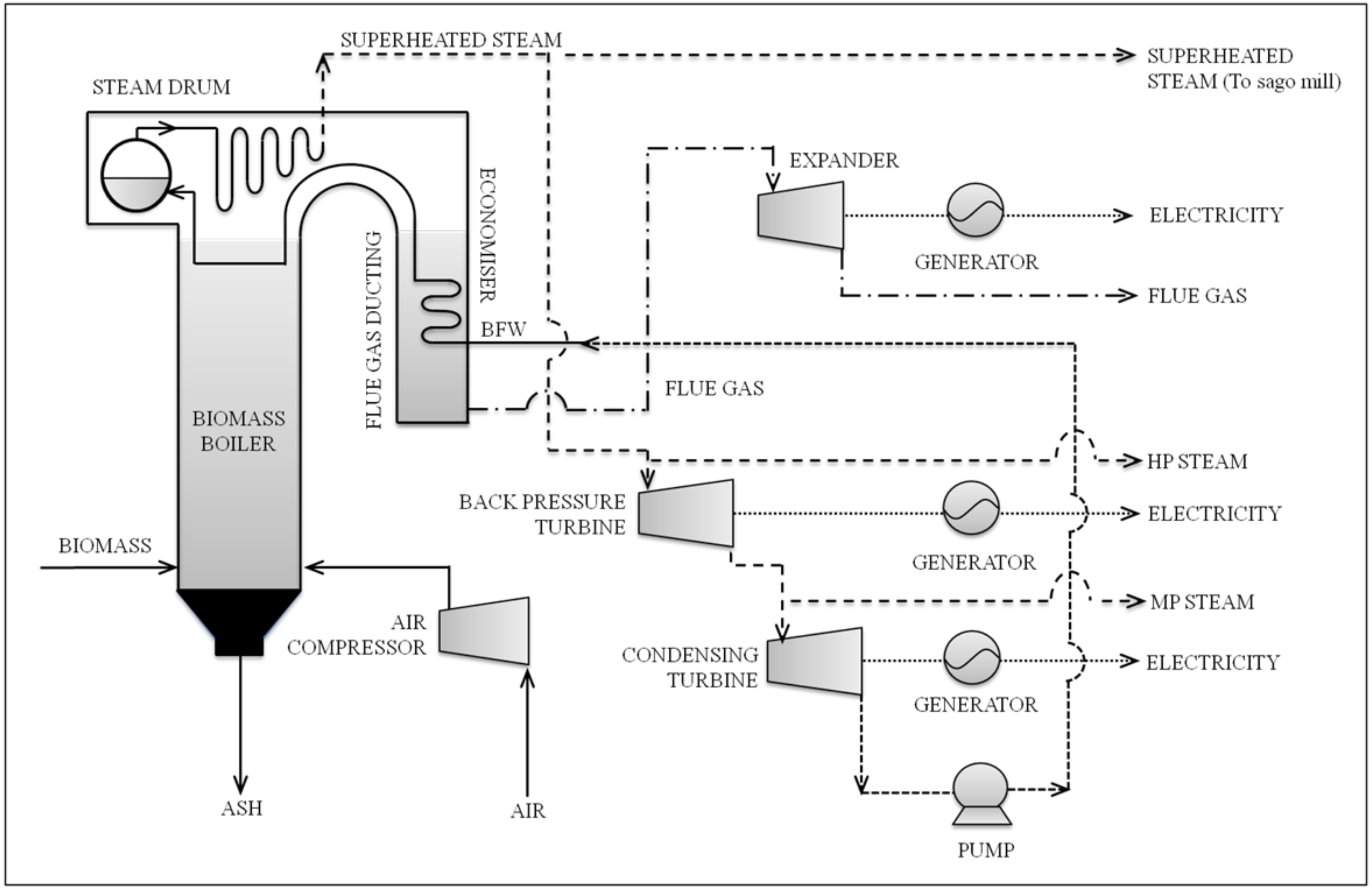

Figure 7.3: Schematic diagram of the biomass CHP system (Configuration 2)

7.4.1.3 Configuration 3: Gasifier-based Biomass CHP System

It is noted that the main concern about Configurations 1 and 2 is the exhaust gas quality. To achieve a cleaner operation and release only clean flue gas to the atmosphere, a gasifier-based CHP system is needed. This gasifier-based CHP system is not only to generate heat and power, but also has two others objectives which are i) production of a cleaner combustible gas, syngas, consisting of carbon monoxide, hydrogen and methane from majority of the carbon and hydrogen contents in biomass (Huang et al., 2013; Sadhukhan et al., 2009) and ii) potential for future expansion by diversifying the products, such as production of biofuel (Fischer-Tropsch liquid) and chemicals (methanol) from syngas via different conversion technologies (Ng and Sadhukhan, 2011a; 2011b). The gas clean-up is also a necessity by the downstream processes, e.g. in case of CHP system, by the gas turbines due to the stricter requirements of the fuel quality. The gas clean-up processes are required to maintain the impurity levels to ppm and ppb levels for trouble free operation of the gas turbines (Sadhukhan et al., 2014). The most effective process is the physical absorption process, e.g. Rectisol^{TM} or Selexol^{TM} that can be used for the removal of whole range of pollutants (e.g. hydrogen sulphide (H_2S), carbonyl sulphide (COS), hydrogen cyanide (HCN), ammonia (NH_3), nickel and iron carbonyls, mercaptans, naphthalene, organic sulphides, etc.) to a trace level in the syngas. The syngas thus generated is an important fuel for the CHP system.

In general, gasifiers are available in fixed bed, moving bed, fluidised bed and entrained bed configurations (Bridgwater et al., 2002). The fixed and moving bed gasifiers need less oxidants, but they require high maintenance cost, produce significant amount of tar and oil and have poor mixing and heat transfer as well as higher risk of agglomeration. In contrast, the fluidised bed gasifier has uniform temperature distribution, good mixing, lower risk of agglomeration and produce less tar and oil (Sadhukhan et al., 2009). Thus the proposed configuration is using the bubbling fluidised bed gasifier. This is followed by gas cooler, gas filter and clean-up, gas turbine, heat recovery steam generator (HRSG) and back pressure and condensate steam turbines as well as air compressors as shown in Figure 7.4. The biomass and compressed air are fed into the gasifier which is connected with a cyclone. Biomass goes through drying, primary pyrolysis or devolatilisation (decomposition under the application of heat), gasification (partial oxidation and reforming) and combustion within the gasifier (Sadhukhan et al., 2014). The operating temperature of the gasifier is 950^{o}C, while the operating pressure is ~25 – 30 bar. The char particles are recirculated in the gasifier reactor and levitated by the product syngas to the top of the gasifier. The particles are recovered by cyclone and the ash is collected in ash grate then taken off from the bottom of the gasifier. The heat of product gas is recovered to generate high pressure steam (at 50 bar or more) in the gas cooler before being washed and treated to produce clean syngas.

Some condensable tar may escape in the gas from the gasifier, which can cause clogging and blockage in piping and filters as well as equipment like turbine. Hence, tar needs to be removed from the gas. To do so, cooling of syngas below its dew point (~60 – 70 ^{o}C) is needed so that the tar is condensed. The effluent water with tar condensates is stored in a settling drum to separate the tar condensates while the water is sent to wastewater treatment plant for water recovery. After the cooling process, the gas is passed through a gas filter to free the remaining dust and particles.

Further, gas clean-up processes (Rectisol™ or Selexol™) may be necessary (for stricter regulations as in the developed nations) to remove chemical pollutants. The clean syngas is then sent to a gas turbine-generator along with excess compressed air for combustion followed by electricity generation. Upon expansion, the resulting exhaust gas is expanded in a HRSG for high pressure steam generation. The superheated steam (at 50 bar and 500^{o}C) from HRSG and syngas cooler is combined and sent to existing sago starch processing facility as required. The remaining steam is then expanded in back pressure and condensate steam turbines, respectively, to generate electricity. Then, the condensates from the turbines are recovered and returned as BFW to the syngas cooler and HRSG. The excess air (approximately 4 times the stoichiometric amount) is needed in the combustor to dilute the gas mixture so that the temperature does not exceed 1250^{o}C to mitigate nitrogen oxides (NO_x) emission (Sadhukhan et al., 2014).

7.4.2 Technical Performance Evaluation

In this chapter, several methods are involved in evaluating the technical performance such as theoretical calculation, excel spreadsheet based calculation, and simulation using Aspen Plus software. Note that technical performance of a CHP system is dependent on total amount of energy and electricity generated from the CHP system. In other words, the higher amount of energy and electricity generated gives the higher technical performance to a CHP system. In order to determine the amount of energy and electricity that can be generated from Configurations 1 and 2, Equation (7.1) is first used to determine the extractable energy from biomass boiler based on boiler efficiency, $\eta_{b'}^{\text{Boiler}}$ where index *b'* represents different types of biomass boiler

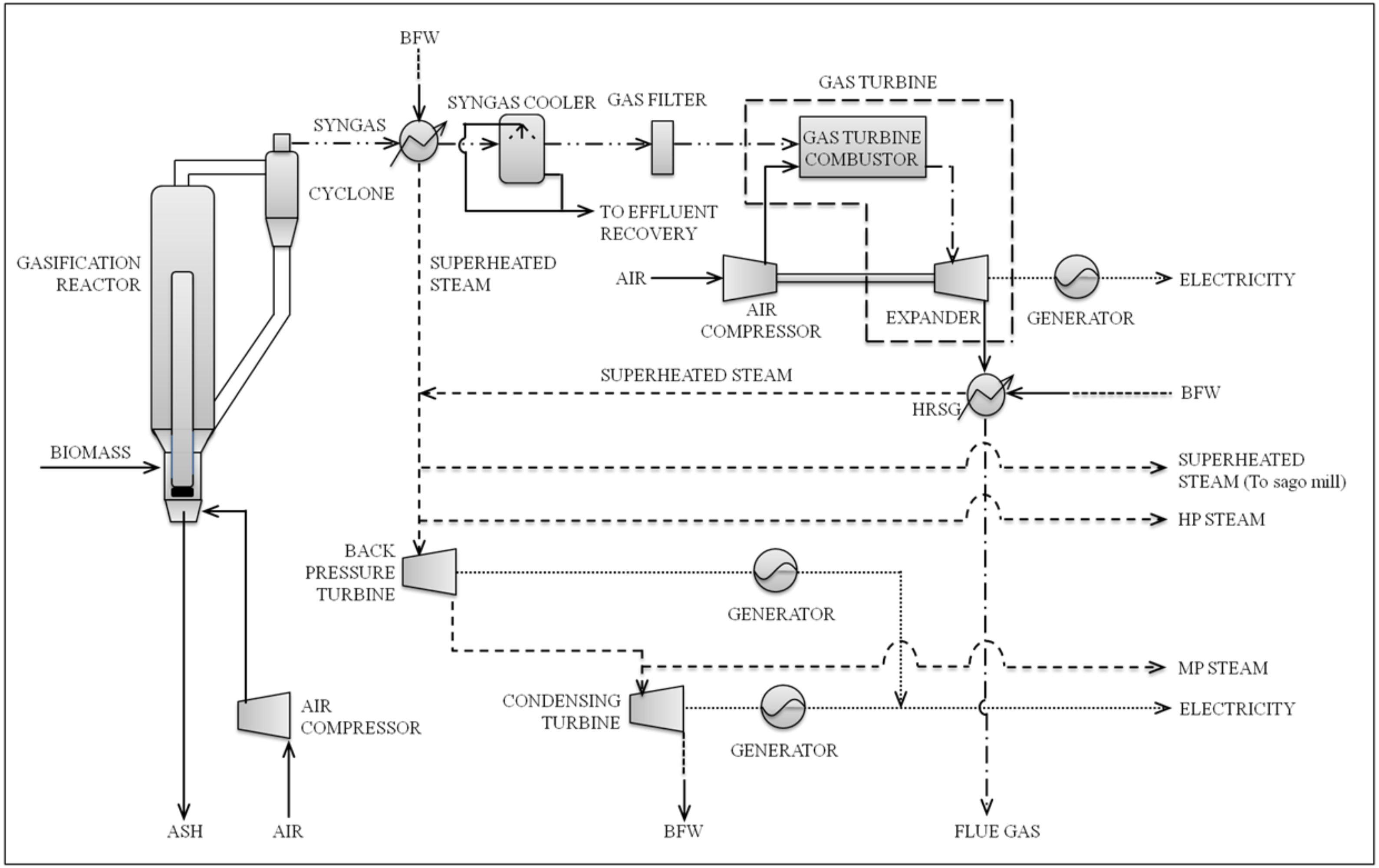

Figure 7.4: Schematic diagram of the biomass CHP system (Configuration 3)

(e.g., normal pressure or pressurised boiler). According to Thornley et al. (2009), the overall energy efficiency of biomass boilers with heat and power production can reach 80-90%. Therefore, in this thesis, 80% of boiler efficiency is used for evaluation.

$$\mathrm{E}_{k,b'}^{\mathrm{Out}} = \mathrm{M}_{k}^{\mathrm{In}} \mathrm{E}_{k}^{\mathrm{In}} \eta_{b'}^{\mathrm{Boiler}} \qquad \forall k \forall b' \qquad (7.1)$$

where $\mathrm{E}_{k,b'}^{\mathrm{Out}}$ is the total extractable energy from biomass *k* via boiler *b'*; while, $\mathrm{E}_{k}^{\mathrm{In}}$ and $\mathrm{M}_{k}^{\mathrm{In}}$ are the calorific value and the intake of biomass *k* fed into the boiler, respectively. Based on the extractable energy, the total mass flow rate of steam generated from biomass *k* and boiler *b'*, $m_{k,b'}^{\mathrm{Steam}}$ can be determined as shown in the following equation:

$$\mathrm{E}_{k,b'}^{\mathrm{Out}} = m_{k,b'}^{\mathrm{Steam}} \left[\mathrm{C_p} \left(\mathrm{T_{sat}} - \mathrm{T_{BFW}} \right) + \Delta \mathrm{h_{vap}} + \left(\mathrm{h_{sup}} - \mathrm{h_v} \right) \right] \qquad \forall k \forall b' \qquad (7.2)$$

where the extractable energy ($\mathrm{E}_{k,b'}^{\mathrm{Out}}$) is used as the heat input for steam generation and C_p is given as the heat capacity of water. Meanwhile, Δh_{vap}, h_v and h_{sup} are the heat of vaporisation of water, specific enthalpy of saturated steam and superheated steam, respectively. Note that, the steam generation is determined based on the following operating conditions:

- Pressure and temperature of the high pressure superheated steam = 50 bar and 500 ^{o}C

- Specific enthalpy of superheated steam, h_{sup} = 3433.7 kJ/kg
- Saturation temperature of steam, $T_{sat,}$ at 50 bar = 264°C
- Specific enthalpy of saturated steam, h_v = 2794.2 kJ/kg
- Temperature of BFW, T_{BFW} = 105 °C
- Heat of vaporisation of water, Δh_{vap} = 1639.6 kJ/kg

A part of the steam flow rate is then supplied to existing sago starch processing facility for starch drying purpose. The remaining steam flowrate can be determined via:

Remaining steam flow rate = total flow rate of steam generation – total steam flow rate supplied to existing sago mill (7.3)

The remaining steam flow rate then forms the basis to determine the electricity generation from back pressure and condensate steam turbines via Aspen Plus software, which is a commercial process simulation tool and has been widely adopted to simulate biomass CHP systems (Huang et al., 2013; Ng and Sadhukhan, 2011a; 2011b), with the following operating conditions.

- Discharge pressure of back pressure steam turbine = 5 bar
- Discharge pressure of condensate steam turbine = 1 bar
- Isentropic efficiency of steam turbines = 80%

Note that, Aspen Plus simulation is used to determine the electricity generation from back pressure turbine, condensate steam turbine, and gas turbine. In this thesis, the discharge pressure and isentropic efficiency of gas turbines are set to the atmospheric pressure and 0.85 (Morita et al., 2004), respectively. Besides, the electricity consumed by air compressors also can be determined via Aspen Plus simulation.

As Configuration 3 has gasification and CHP modules, a modular process flow sheet is simulated using Aspen Plus to establish mass and energy balances. The method used in this case is adopted from the work by Sadhukhan et al. (2009). The fluidised bed gasifier is simulated by two RGibbs reactors in Aspen Plus, a gasifier with gas and tar input and a char combustor. The RGibbs reactor model in Aspen Plus estimates product compositions for the minimum Gibbs free energy change of reactions. Thus, only the feed flows (in this case gas, tar and char), compositions, temperature and pressure conditions and the RGibbs reactors' operating temperature and pressure conditions need to be specified in Aspen Plus model to estimate the resulting syngas composition. Since the actual gasification reactions take place after the primary pyrolysis occurs, the products of primary pyrolysis (gas, tar and char) were considered as feeds to the two RGibbs reactors, gas and tar to the gasifier and char to the char combustor (Sadhukhan et al., 2014). The compositions of the feeds to both RGibbs reactors in Aspen Plus simulation are predicted using spreadsheet based yield models (Sadhukhan et al., 2009), based on the data shown in Table 7.1.

Air is added for the char combustor to fully combust char and thereby supplying the heat for the steam reforming reaction in the gas and tar gasifier. The following gasifier and char combustor process operating conditions are set in Aspen Plus simulation.

- Input flowrate of air to gasifier = 0.47 t/d
- Input flowrate of air to char combustor = 4.15 t/d
- Input flowrate of air to gas turbine combustor = 83.10 t/d
- Discharge pressure and isentropic efficiency of air compressors = 30 bar and 0.7
- Pressure and temperature of gasifier and combustor = 30 bar and 950 ^{o}C
- Pressure and exit temperature of the gas from the cooler = 30 bar and 65 ^{o}C
- Discharge pressure of the gas expander = 1 bar
- Outlet temperature of the exhaust gas from the HRSG = 120 ^{o}C

Table 7.1: Ultimate analysis, proximate analysis and calorific value of sago biomass

	Sago Barks	Sago Fibres
[1]Ultimate analysis (wt%)		
Carbon (C)	43.23	41.82
Hydrogen (H)	5.71	6.06
Oxygen (O)	50.65	51.97
Nitrogen (N)	0.42	0.14
Sulfur (S)	0.00	0.00
[1]Proximate analysis (wt%)		
Moisture	2.76	4.19
Volatile Matter	54.12	77.14
Fixed C	4.30	2.76
Ash	38.82	15.91
Calorific value (kJ/g)	[1]19.27	[3]14.25
[2]Available amount of biomass (wet basis) (t/d)	20.80	16.90
[3]Moisture content of wet biomass (%)	51.00	62.00
[4]Available amount of biomass (dry basis) (t/d)	10.20	6.40

[1]Data is obtained from lab test results from University Putra Malaysia; [2]data is deduced from Adeni et al. (2009); [3]Data is obtained from lab test results from The University of Nottingham Malaysia Campus; [4]Data is estimated based on the moisture content of respective wet biomass as shown in the Table.

A stoichiometric amount of air is specified for full combustion of the char and the heat balance between the gas and tar gasifier (endothermic) and char combustor (exothermic). Air is then used as the external oxidising agent for the reactions above. In addition, adiabatic condition for the gas turbine combustor (RGibbs reactor) is specified and the air intake is increased to limit the temperature of the combustor at 1250°C in order to mitigate NO_x emission. Based on the data given above, the CHP system is simulated using Aspen Plus simulation software. Based on the results obtained from Aspen Plus software, the total heat generated from the cooler and HRSG and electricity generated from the gas turbine is then determined. Once the heat generated from CHP system is determined, steam generation is then determined using Equation (7.2). Then, based on the determined steam generation, the electricity generation from the back pressure and condensate steam turbines with operating conditions shown earlier are determined using Aspen Plus simulation.

7.4.3 Environmental Performance Evaluation

Based on the determined amount of total electricity generation, environmental performance of each configuration, which is based on carbon saving (*CS*), can be determined via following equation:

$$CS_c = ELEC_c \times \mathrm{EF}^{\mathrm{ELEC\_FS}} \times \mathrm{OPH}_c \qquad \forall c \qquad (7.4)$$

where CS_c and $ELEC_c$ are the carbon saving and generated electricity of configuration *c*, respectively. Meanwhile, $\mathrm{EF}^{\mathrm{ELEC\_FS}}$ is the carbon emission factor of electricity generation from fossil fuel in Malaysia (0.899 kg CO_2/kWh determined in

Chapter 4) and OPH_c is the operating hours of configuration *c* (20 h). Note that the emissions of the flue gases released from all the configurations of CHP systems are not included in this environmental performance evaluation as the flue gases generated from biomass are CO_2-neutral (Tan and Foo, 2007). Thus, in this work, only the carbon saving on the product (electricity) for replacement of fossil fuel for electricity generation is taken into consideration.

7.4.4 Economic Performance Evaluation

The economic performance evaluation is carried out for each configuration of CHP system after the mass and energy balance analysis is completed and the sizes of the equipment are determined, in order to investigate the viability of the CHP system configurations. This thesis adopts the methodology discussed in Sadhukhan et al. (2014). First, a list of equipment with desired sizes is prepared. Then, by applying the concept of economy of scale, the base cost of equipment with a specific size adopted from Sadhukhan et al. (2014) is scaled up or down to obtain the cost of equipment for the desired size. Note that, the scale factor is adapted from Sadhukhan et al. (2014). In order to update the cost of equipment from their given base years, Chemical Engineering Plant Cost Index of year 2014 (574.4) is used in this work. Guthrie's method is then applied to determine the total capital investment (TCI) using installation factors of individual unit operations obtained from Sadhukhan et al. (2014). The desired equipment capacity and TCI of equipment are summarised in Table 7.2. In order to determine the TCI of each configuration, the relevant equipment capital costs are assimilated and added up.

Next, total operating cost, which is equal to 1.2 – 1.3 times of the direct production cost, is determined (Sadhukhan et al., 2014). In this thesis, an average 1.25 times of the direct production cost is used to determine the total operating cost. Note that direct production cost is the summation of fixed and variable operating costs. In order to determine the variable operating cost, biomass feedstock cost and transportation cost are first determined. In this chapter, the CHP system is assumed

Table 7.2: Equipment design capacity and total capital investment cost (Malaysia Context).

	Equipment	Design capacity		§Total capital investment (million USD)
Pre-treatment	Conveyers	0.87	Wet t/h	0.0019
	Grinding	0.87	Wet t/h	0.0047
	Storage	0.87	Wet t/h	0.0096
	Dryer	0.87	Wet t/h	0.0423
	Iron removal	0.87	Wet t/h	0.0030
	Feeding system	0.87	Wet t/h	0.0011
CHP system (Configuration 1)	Biomass boiler*	0.62	kg/s	0.4323
	Steam turbine*	231	kW	0.2371
	Condensate turbine*	241	kW	0.2414
CHP system (Configuration 2)	Biomass boiler*	0.56	kg/s	0.4972
	Air compressors	255	kW	0.2032†
	Gas turbine	189	kW	1.2722
	Steam turbine*	200	kW	0.2227
	Condensate turbine*	210	kW	0.2274
CHP system (Configuration 3)	Gasifier	0.43	Dry t/h	2.7024
	Air compressor	37	kW	0.0940†
	Air cooler	0.06	kg/s	0.3919
	Gas turbine	798	kW	1.7268
	Air compressor	689	kW	0.1879†
	Steam turbine*	32	kW	0.1004
	Condensate turbine*	38	kW	0.1368

**The capital cost of equipment is estimated based on the design capacity using correlations presented by Peter et al. (2002); †The capital cost of equipment is estimated based on the design capacity supplied by Malaysia's equipment supplier; §USD 1.0 = RM 3.2*

as a standalone facility and hence the biomass is bought from the sago starch extraction process (SSEP) either in wet or dry basis depending on whether or not the biomass pre-treatment is available in the CHP system. For the CHP system without pre-treatment, dried biomass is purchased so that it can be used as fuel source directly in the CHP system. For the CHP system completed with pre-treatment, wet biomass is purchased, as the wet biomass is cheaper and can be dried, grinded, demineralised in its own pre-treatment before feeding into the CHP system. As the biomass price is volatile, the price ranges should be considered in the sensitivity analysis. In this chapter, the range of dried and wet feedstock costs are given as USD 50 – USD 110 per tonne (Ng et al., 2014) and USD 10 – USD 50 per tonne (Ng et al., 2014), respectively. In this chapter, these costs included the collecting cost of biomass for the CHP system. In addition, an average local transportation cost for biomass feedstock is assumed at USD 0.60/GJ (Sadhukhan et al., 2014).

On the other hand, the fixed operating cost includes the costs of maintenance, personnel, laboratory, supervision, plant overheads, capital charges, insurance, local taxes, royalties, sale expense, general overheads and research and development (Sadhukhan et al., 2014). These costs are determined based on the labour cost and indirect capital cost. The working hours and salary of each worker are assumed 3330 h/y and USD 10 per hour. The CHP system is operated average 20 hours a day and hence two shifts per day and one worker per shift are assumed. Note that two scenarios are considered in this chapter to examine the importance of integration of CHP system and SSEP, and to evaluate the impact of labour cost on the economic performance of a CHP system. In case where the CHP system is standalone, hiring new labour (HL) is required and thus additional labour cost is considered in the analysis. In contrast, in case where the CHP system is integrated with SSEP and making use of current labour (UCL) from SSEP, no additional of labour cost will be considered in this evaluation. On the other hand, Lang's method is used to determine the indirect capital cost. Besides, in order to determine the revenue, USD 0.095/kWh (USD 1 = RM 3.2) of electricity selling price (Andiappan et al., 2014) and USD 0.026/kg (USD 1 = RM 3.2) of steam selling price are used in this chapter. In this chapter, it is assumed that the CHP system is installed next to the sago starch processing facility and hence the steam could be sent and sold to sago starch processing facility by installing a piping system. Based on these data, the profit and payback period of each configuration can be determined.

7.5 Results and Discussion

7.5.1 Technical and Environmental Performance

The technical and environmental performance of each configuration using sago barks and sago fibres as feedstock is shown in Table 7.3. As shown, the configurations using sago barks as feedstock have greater net energy and electricity generation regardless of the presence of pre-treatment in CHP compared to sago fibres. This is due to higher calorific value of sago barks compared to sago fibre. Besides, by using sago barks as feedstock, Configuration 1 has the highest energy and electricity generations (bold in Table 7.3) among the configurations and this is followed by Configuration 2 and Configuration 3. Although the total electricity generation from Configuration 2 (599 kW) is higher compared to Configuration 1 (472 kW), after considering the consumption of electricity in the CHP system, the net electricity generation from Configuration 2 is lower than Configuration 1. This is due to consumption of some generated electricity by air compressor (255 kW) in Configuration 2 as shown in Table 7.3. Besides, when barks are used as feedstock, it is also found that Configurations 3 has the lowest net energy and electricity

Table 7.3: Technical and environmental performance of Configurations 1, 2 and 3 with sago barks and fibres feed.

	Configuration 1		Configuration 2		Configuration 3	
	Barks	Fibres	Barks	Fibres	Barks	Fibres
Energy intake (kW)	2276	1065	2276	1065	2276	1065
Energy (heat + electricity) generation (kW)						
• Boiler	1820	852	1642	699	N/A	N/A
• Gas cooler	N/A	N/A	N/A	N/A	183	176
• HRSG	N/A	N/A	N/A	N/A	508	470
• Gas turbine	N/A	N/A	189	169	956	892
• Compressor	N/A	N/A	-255	-216	-709	-667
Net energy (kW)	1820	852	1576	652	938	871
Heat input for steam generation (kW)	1820	852	1642	699	691	646
Total steam generated (kg/d)	44,482	20,815	40,126	17,086	16,898	15,804
Total electricity can be generated (kW)	646	302	772	417	1202	1122
Superheated steam (to sago mill) (500^{o}C, 50 bar) (kg/d)	12,816	12,816	12,816	12,816	12,816	12,816
HP steam (to sago mill) (kg/d)	0	0	0	0	0	0
MP steam (to sago mill) (kg/d)	0	0	0	0	0	0
Remaining steam (kg/d)	31,666	7999	27,310	4270	4082	2988
Total electricity generated from remaining steam (kW)	472	140	599	259	1026	962
Total electricity consumed (on- / off-site pre-treatment) (kW)	-55 / 0	-55 / 0	-310 / -255	-271 / -216	-764 / -709	-722 / -667
Net electricity generated (on- / off-site pre-treatment) (kW)	417 / 472	85 / 140	289 / 344	-12 / 43	262 / 317	240 / 295
Environmental performance (carbon saving) (on- / off-site pre-treatment) (kgCO_2/d)	7498 / 8487	1528 / 2517	5196 / 6185	-216 / 773	4711 / 5700	4315 / 5304

Note: on-site pre-treatment = completed with implementation of pre-treatment; off-site pre-treatment = without implementation of pre-treatment.

generations. This is due to high amount of direct use of electricity by air compressors (709 kW).

On the other hand, Configuration 1 has the highest environmental performance as it has the highest net electricity generated and the highest carbon saving regardless existence of pre-treatment. As shown, for the scenario where CHP system with off-site pre-treatment, the carbon saving of configuration 1 using sago barks as feedstock has the highest environmental performance (8,487 kgCO_2/d). This is followed by Configuration 2 (6,185 kgCO_2/d) and Configuration 3 (5,700 kgCO_2/d) with sago barks as feedstock. These results clearly show that configuration 1 has the highest technical and environmental performance among the configurations. Besides, the results also showed that sago barks have the highest energy and environmental performance compared to sago fibres. Therefore, only sago barks are used in the following economic performance evaluation to reduce the complexity of analysis and demonstration.

7.5.2 Economic Performance

Since using sago barks as feedstock in the CHP system gives better technical and environmental performance compared to sago fibres, sago barks are chosen for detailed economic evaluation for all the selected CHP configurations. In this chapter, the economic evaluation considered different scenarios such as with on-site or off-site pre-treatment in the CHP system, hiring new labour (HL) or making use of current labour (UCL) from SSEP for CHP system. Note that cost analyses in many previous studies did not include these scenarios (TeymouriHamzehkolaei and Sattari, 2011; Ren and Gao, 2010; Treshchev et al., 2010; Mago et al., 2010; Moreton and Rowley, 2012; Anderson and Toffolo, 2013; Celma et al., 2013). Note also that the main purpose of comparing the results between HL and UCL is to evaluate the significant effect of labour cost on economic performance of CHP system. Based on the data input as given in Tables 7.1 and 7.2 and the methodology discussed in Section 7.4.4, the profitability analyses of Configurations 1, 2 and 3 with on-site and off-site pre-treatment, and with HL or UCL were carried out and the results are summarised in Table 7.4. As shown, Configuration 1 has the lowest payback period and highest profit in all the scenarios. In addition, most of the configurations are not viable (payback period close to 25 years or above) when HL is performed or additional labour cost is considered in the CHP system except the Configuration 1 as shown in Table 7.4.

Table 7.4 also shows that in the case without consideration of additional labour cost or making use of current labour from SSEP, Configuration 1 with on-site pre-treatment has lower payback period of 2.51 years and higher annual profit of USD 0.3872 million/y compared to the case with off-site pre-treatment resulted in a payback period of 3.51 years and annual profit of USD 0.2596 million/y, respectively. For Configuration 2, the CHP system with on-site and off-site pre-treatment has 9.08 years and 16.58 years of payback period, respectively. Besides, Configuration 3 has a payback period of 25 years and above as shown in Table 7.4. Note that the scenarios with payback period less than 25 years are considered as economically feasible scenarios. All the relevant data (i.e., net electricity generated, carbon saving, and payback period) of these economic feasible scenarios are extracted and summarised in Table 7.5.

Table 7.4: Results of profitability analyses of Configurations 1, 2 and 3 for the cases with on-site and off-site pre-treatment, hiring new labour (HL) or making use of current labour (UCL) (Malaysia context).

Configuration (with hiring new labour (HL))	CHP system with off-site pre-treatment			CHP system with on-site pre-treatment		
	1	2	3	1	2	3
Total capital investment (million USD)	0.9108	2.4226	5.3402	0.9734	2.4852	5.4028
Annualised capital cost (million USD /y)	0.0577	0.1534	0.3382	0.0617	0.1574	0.0342
Fixed operating cost (million USD /y)	0.1342	0.1452	0.1665	0.1346	0.1457	0.1669
Variable operating cost (million USD /y)	0.1780	0.1802	0.1876	0.0421	0.0443	0.0517
Direct production cost (million USD /y)	0.3122	0.3254	0.3541	0.1767	0.1900	0.2186
Total operating cost (million USD /y)	0.3902	0.4068	0.4426	0.2209	0.2375	0.2733
Revenue (million USD /y)	0.4905	0.3934	0.3730	0.4487	0.3517	0.3312
Profit (million USD /y)	0.1002	(0.0133)	(0.0696)	0.2278	0.1142	0.0579
Payback period (y)	9.09	N/A	N/A	4.27	21.76	> 25
Configuration (making use current labour (UCL))	CHP system with off-site pre-treatment			CHP system with on-site pre-treatment		
	1	2	3	1	2	3
Total capital investment (million USD)	0.9108	2.4226	53402	0.9734	2.4852	5.4028
Annualised capital cost (million USD /y)	0.0577	0.1534	0.3382	0.0617	0.1574	03422
Fixed operating cost (million USD /y)	0.0064	0.0177	0.0389	0.0071	0.0181	0.0394
Variable operating cost (million USD /y)	0.1780	0.1802	0.1876	0.0421	00443	0.0517
Direct production cost (million USD /y)	0.1844	0.1979	0.2265	0.0492	0.0624	0.0911
Total operating cost (million USD /y)	0.2308	0.2473	0.2831	0.0615	0.0780	0.1138
Revenue (million USD /y)	0.4905	0.3934	0.3730	0.4487	0.3517	0.3312
Profit (million USD /y)	02596	0.1461	0.0898	0.3872	0.2736	0.2174
Payback period (y)	3.51	16.58	> 25	2.51	9.08	24.86

Note: on-site pre-treatment = completed with implementation of pre-treatment; off-site pre-treatment = without implementation of pre-treatment; USD 1.0 = RM 3.2

Table 7.5: Data summary for economic feasible scenarios

Relevant data	Payback period (year)			Net electricity generated (kW)			Carbon saving ($kgCO_2/d$)		
Scenarios \ Configurations	1	2	3	1	2	3	1	2	3
HL and on-site pre-treatment	4.27	21.76	N/A	417	289	N/A	7498	5196	N/A
UCL and on-site pre-treatment	2.51	9.08	24.86	417	289	262	7498	5196	4711
HL and off-site pre-treatment	9.09	N/A	N/A	472	N/A	N/A	8487	N/A	N/A
UCL and off-site pre-treatment	3.51	16.58	N/A	472	344	N/A	8487	6185	N/A

Note: HL = hiring new labour; UCL = use current labour; on-site pre-treatment = completed with implementation of pre-treatment; off-site pre-treatment = without implementation of pre-treatment.

As shown, there are 4 scenarios in each configuration:

- Hiring new labour (HL) and completed with on-site pre-treatment
- Use current labour (UCL) and completed with on-site pre-treatment
- Hiring new labour (HL) and with off-site pre-treatment
- Use current labour (UCL) and with off-site pre-treatment

It is found that Configuration 1 is the configuration of CHP system with the lowest payback period regardless with on-/off-site pre-treatment. Therefore, Configuration 1 is further analysed for its sensitivity on payback period with respect to feedstock costs.

7.6 Sensitivity Analysis for Different Scenarios

Results of sensitivity analysis on payback period have been summarised and shown in Figure 7.5 to Figure 7.8. As shown in Figure 7.5, less than 5 years of payback period can be achieved when new labour is hiring for the CHP system with off-site pre-treatment, and using lowest purchased cost of bark (USD 50 per tonne) and 90% efficiency of boiler. As expected, this payback period is increased to 6 or 9 years when lower boiler efficiency (80%) is used. 6 – 22 years of payback period was estimated for combined biomass (barks and fibres) and 80% efficiency of boiler. This payback period drops to 4 – 10 years when boiler efficiency is 90%.

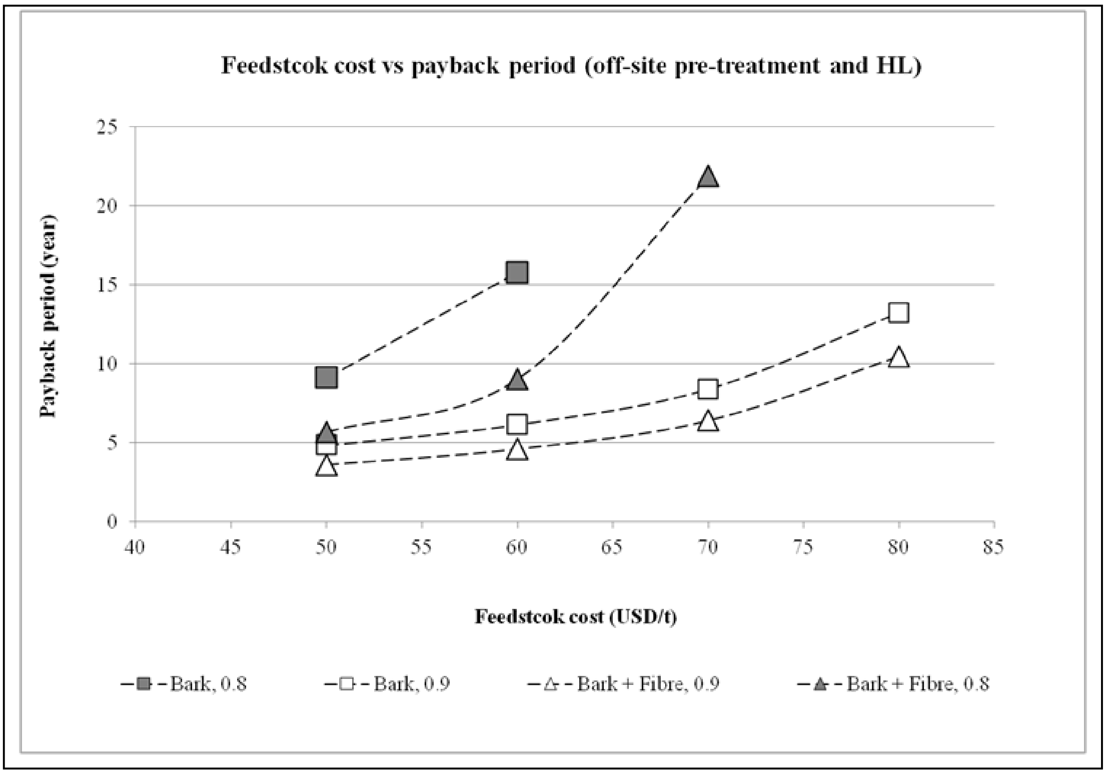

Figure 7.5: Feedstock cost versus payback period in scenario off-site pre-treatment and with hiring new labour (HL)

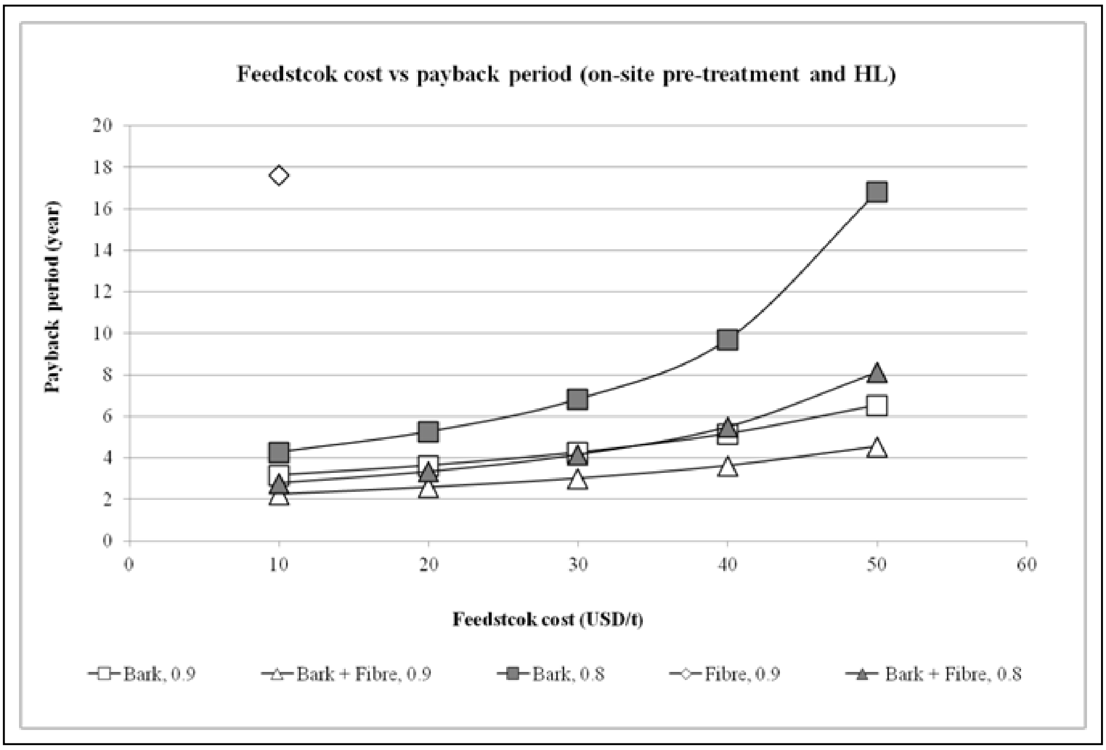

Figure 7.6: Feedstock cost versus payback period in scenario on-site pre-treatment and with hiring new labour (HL)

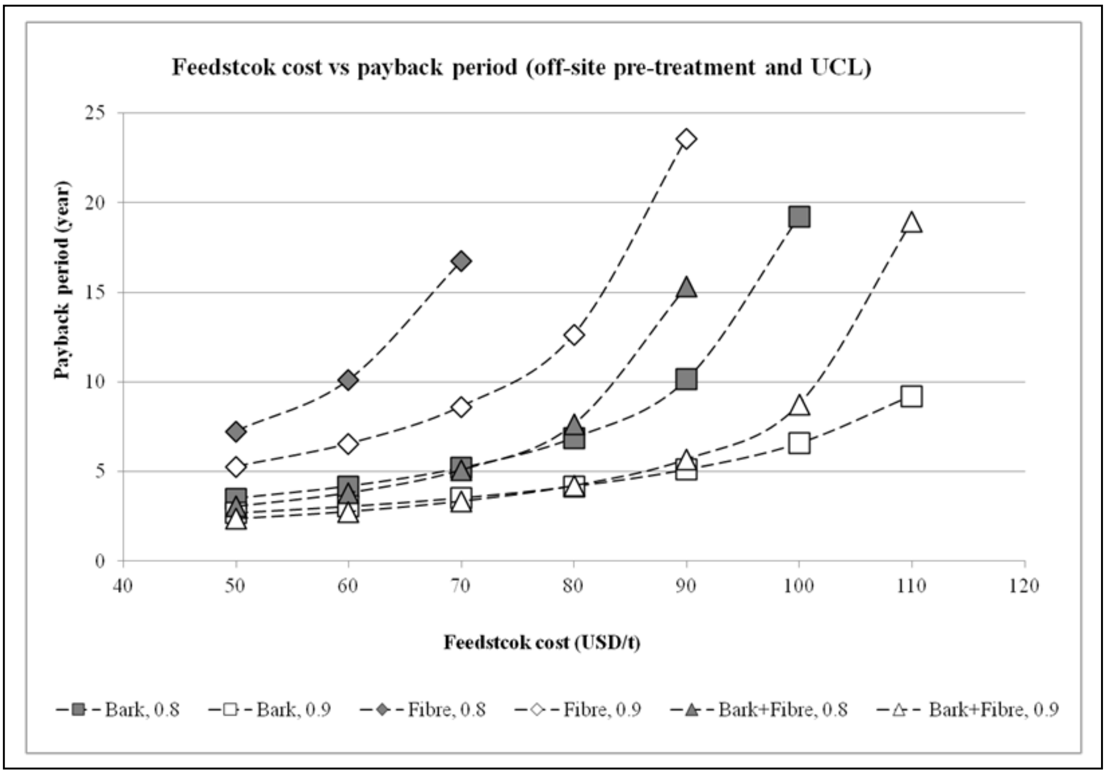

Figure 7.7: Feedstock cost versus payback period in scenario off-site pre-treatment and using current labour (UCL)

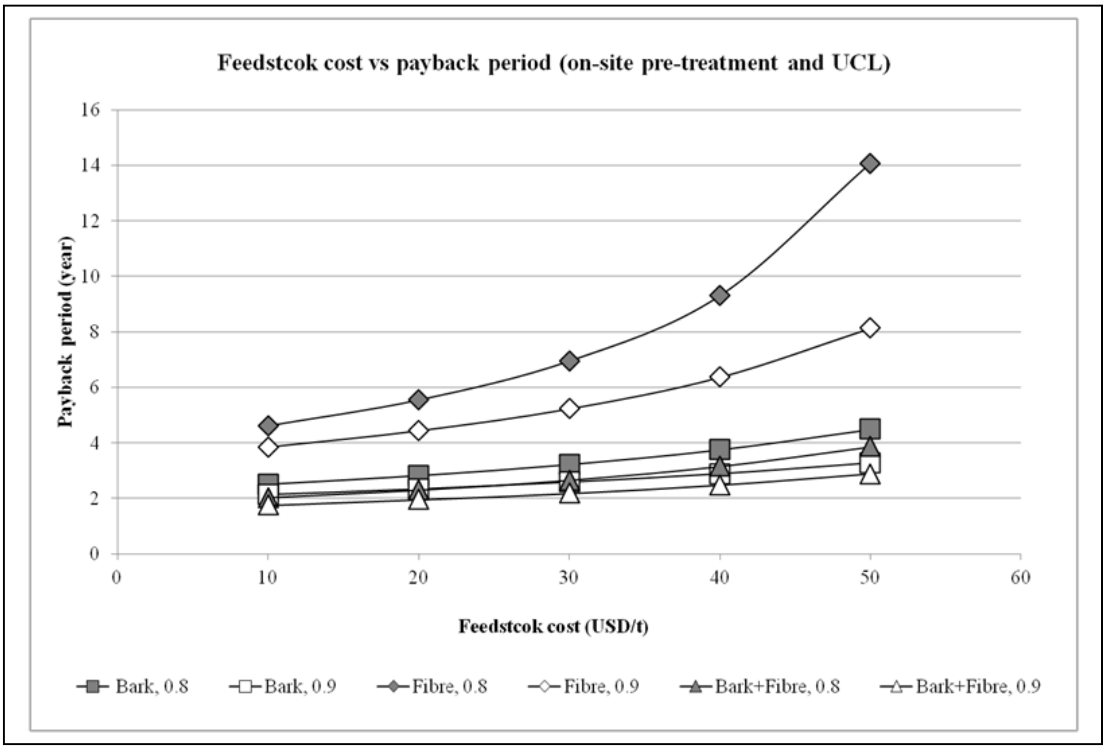

Figure 7.8: Feedstock cost versus payback period in scenario on-site pre-treatment and using current labour (UCL)

For the scenario the CHP system completed with on-site pre-treatment and fed with sago fibre as well as hiring new labour, payback periods of ~18 years were estimated as shown in Figure 7.6. In contrast, by using sago barks and combined biomass in 90% efficiency boiler, much lower ranges of payback period, 3 – 7 years and 2 – 5 years, respectively, were estimated for a feedstock cost of USD 10 – USD 50 per tonne, respectively.

Sensitivity analyses for the scenario where on-site or off-site pre-treatment is implemented, and current labour from SSEP is used as shown in Figure 7.7 and Figure 7.8. Figure 7.7 shows the cases of the CHP system with off-site pre-treatment and making use of current labour. As shown, a payback period of less than 5 years is predicted for the case using a boiler efficiency of 90%, sago bark and combined biomass as feedstock, and lower feedstock cost (USD 50 – 70/t). As expected sago fibre shows least favourable economics.

In the cases, CHP system completed with on-site pre-treatment and making use of current labour as shown in Figure 7.8, their payback period is the lowest. For instance, 1.8 – 2.9, 2.0 – 3.3, and 3.8 – 8.0 years of payback period can be achieved by the CHP system using feedstock of combined biomass, sago bark, and sago fibre, respectively. Based on these sensitivity analysis results shown in Figure 7.5 to Figure 7.8, it is noted that labour cost has significant impact on viability and payback period of CHP system. Thus, it is important to pay due attention to the labour cost for development of new CHP system.

Figure 7.9 shows the accumulated profit for the configurations with on-site and off-site pre-treatment and without consideration of additional labour cost (use current labour). Note that most of the cases which considered additional labour cost (hiring new labour) in CHP system have negative profit and hence only the cases making use of current labour are shown in Figure 7.9. As shown, the CHP system with on-site pre-treatment has the highest accumulated profit in long term running.

In addition, combined biomass has the highest accumulated profit (USD 15.81 million) which is followed by sago barks (USD 10.68 million) and sago fibre (USD 4.11 million), over 25 years. Hence, pre-treatment is important to be implemented in a CHP system to achieve higher economic performance.

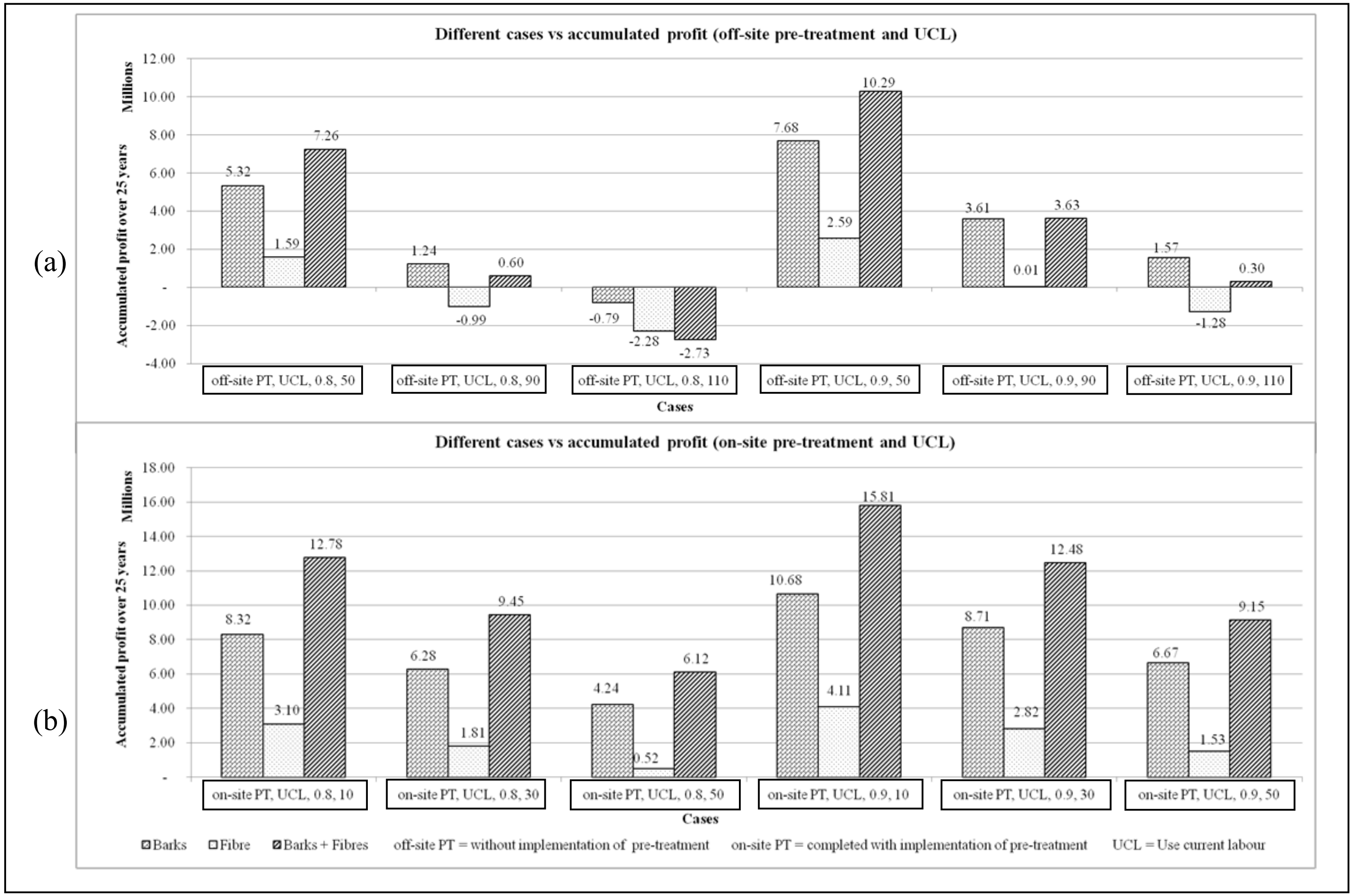

Figure 7.9: Different cases versus accumulated profit in scenario with on-site and off-site pre-treatment and with UCL

7.7 Summary

In this chapter, techno-economic and environmental performance of sago biomass-based CHP systems is evaluated to examine its technical and economic feasibility. Various configurations (with normal pressure boiler, pressurised boiler and bubbling fluidised bed gasifier) using various sago biomass (sago barks or sago fibres) as fuel sources are taken into consideration. In addition, different scenarios (i.e., on-site and off-site pre-treatment, hiring new labour or making use of current labour from SSEP) are also evaluated. Besides, a generic techno-economic evaluation framework is developed in this chapter to select the CHP system with the lowest payback period. As results, CHP system with normal pressure boiler (configuration 1) is found has the lowest payback period (2.51 years) regardless with on-/off-site pre-treatment. On the other hand, a sensitivity analysis is conducted in different scenarios due to variation in feedstock cost. It is found that labour cost and existence of pre-treatment has significant impact on feasibility and payback period of CHP system. Thus, it is important to pay due attention to the labour cost and existence of pre-treatment for development of new CHP system.

CHAPTER 8

TECHNO-ECONOMIC EVALUATIONS FOR FEASIBILITY OF SAGO-BASED BIOREFINERY, PART 2: INTEGRATED BIOETHANOL PRODUCTION AND ENERGY SYSTEMS

8.1 Introduction

In this chapter, the techno-economic evaluation performed in Chapter 7 is extended to examine the feasibility of integrated sago-based bioethanol production and energy systems. A conceptual integrated sago-based biorefinery (SBB) is envisioned and analysed based on the bioethanol plant study conducted by the National Renewable Energy Laboratory (NREL). The techno-economic performance of the integrated SBB as well as its environmental performance is evaluated. For the performance evaluations, various feedstocks such as sago fibres, barks, and combined biomass (fibres and barks) are considered. The integrated SBB with the highest technical performance (highest yield of bioethanol and electricity production), is then selected for detailed economic analysis. Since sago biomass could be used as raw material to produce cellulase enzyme that is required in hydrolysis process for bioethanol production (Linggang et al., 2012), scenarios with on-site and off-site enzyme production are considered in the evaluations. In this chapter, on-site enzyme production is referred to all enzyme is produced in sago-based biorefinery plant (SBP). In contrast, off-site enzyme production is referred to all the required enzymes are purchased from suppliers. Besides, the impacts of labour cost on the economic performance of the integrated SBB, is also evaluated. In this chapter, a small scale sago mill (12 t/d) from Sarawak, Malaysia, used as case study in previous chapters, is adopted for evaluation.

8.2 Process Description: Integrated Sago-based Biorefinery (SBB)

Integrated sago-based biorefinery (SBB) consist of sago starch extraction process (SSEP), sago-based bioethanol plant (SBP), combined heat and power (CHP) system, and wastewater treatment plant (WWTP) as shown in Figure 8.1.

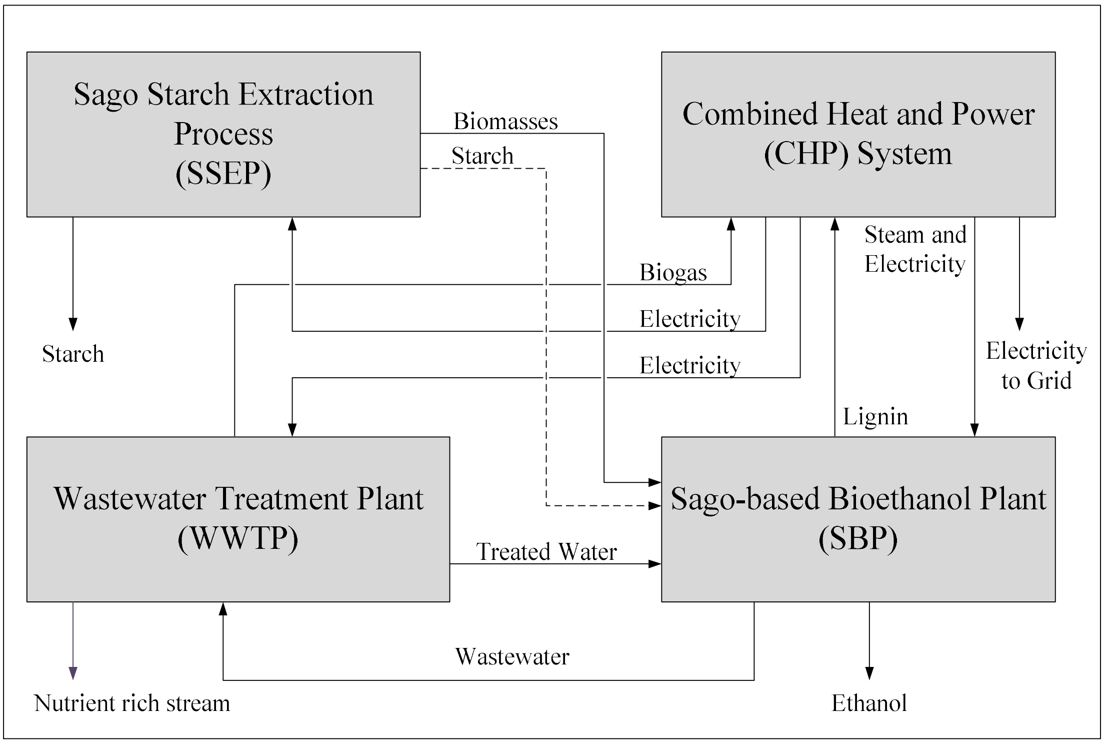

Figure 8.1: Conceptual block diagram of integrated sago-based biorefinery (SBB)

In SBP, sago biomass can be converted into bioethanol. The resulting wastewater and lignin are sent to the WWTP and CHP system, respectively. In the CHP system, the lignin and biogas (produced from the WWTP) are used as fuel sources to generate steam and electricity. The generated steams are used in SBP to fulfil the process steam requirement before being used for electricity generation. The generated electricity is then supplied to the SBP, WWTP and existing SSEP for self-sustenance. Excess electricity (if any) can be sold to the grid to increase the overall economic performance of the integrated SBB. Meanwhile, the wastewater is sent to the WWTP to generate biogas and then being treated to meet the discharge regulation. The treated water can then be recycled to SBP to reduce the freshwater consumption.

8.2.1 Sago-based Bioethanol Plant (SBP)

In this chapter, a biochemical conversion technology studied by NREL and Harris Group Inc., (Humbird et al., 2011) is adopted for conversion of sago biomass into bioethanol. In this technology, there are few main processes involved to convert the biomass into bioethanol, such as pretreatment, enzymatic hydrolysis, fermentation processes, and bioethanol recovery process (Figure 8.2). In the first stage of pretreatment process, sago biomass is fed to a pretreatment reactor and mixed with diluted sulphuric acid (18 mg acid/dry g of biomass) that catalyses the hydrolysis reaction at a temperature of 158 ^{o}C. High pressure (13 bar) steam is used in this stage to maintain the temperature. Most of the hemicellulose carbohydrates such as xylan in biomass are converted into xylose oligomers within a short residence time of 5 minutes. Some other minor hemicellulose carbohydrates (arabinan, mannan and galactan) have the same reactions and conversions as xylan. The resulting slurry goes into a second stage of pretreatment, oligomer conversion step, where most of the xylose oligomers from the first stage are converted into monomeric xylose at a

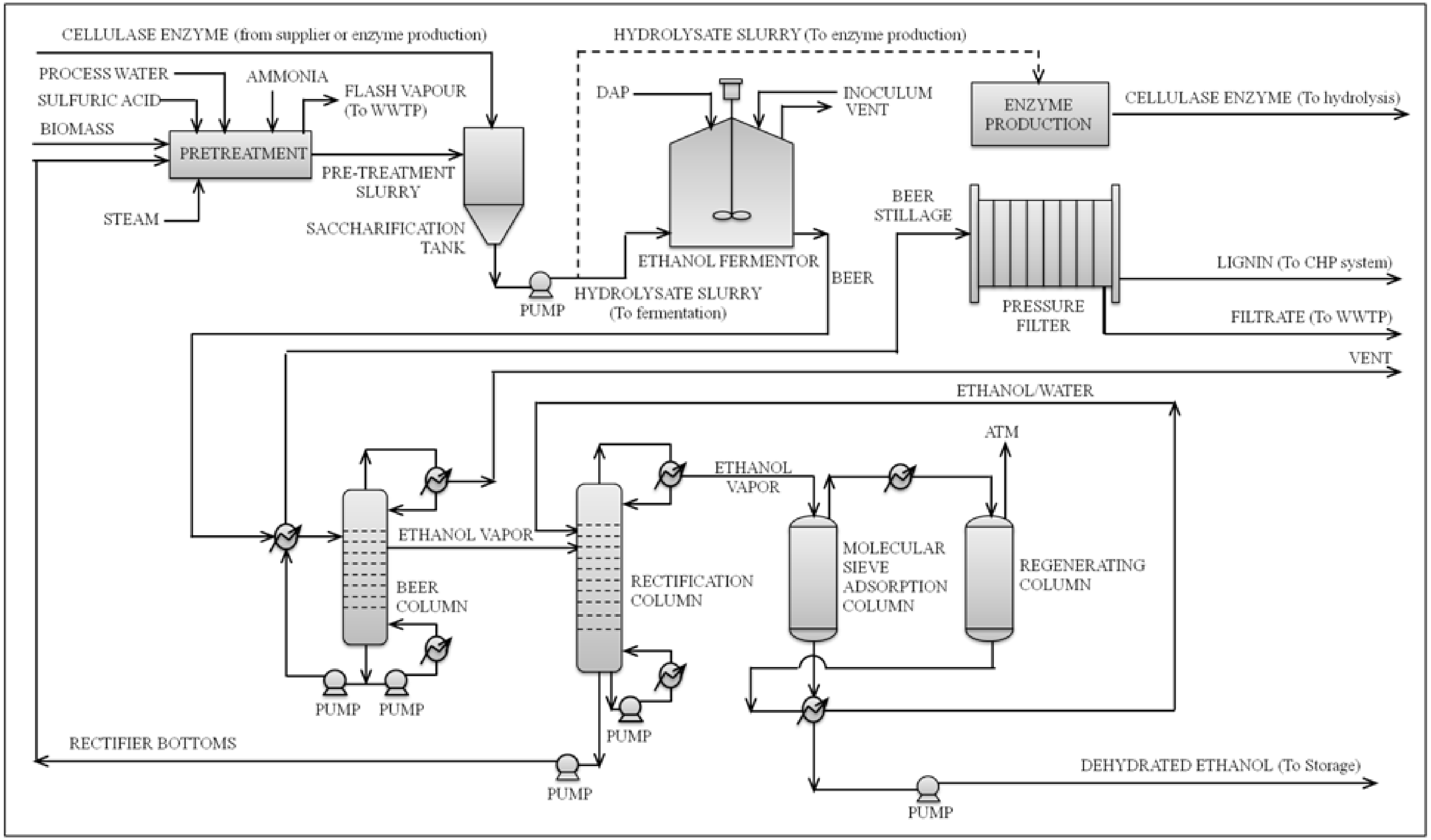

Figure 8.2: Configuration of sago-based bioethanol plant (SBP)

temperature of 130 ^{o}C and residence time of 20 – 30 minutes. The slurry is then flashed at atmospheric pressure. After the flash, the slurry containing 30 wt% of total solids is sent to a conditioning reactor, where water and ammonia are added to dilute the solid content to approximately 20 wt% and to increase the pH of the slurry to 5 – 6 to ensure miscibility for enzymatic hydrolysis. The slurry is cooled to 75 ^{o}C after a total conditioning residence time of 30 minutes. Note that ammonia helps to avoid sugar losses and eliminate the solid–liquid separation steps. This makes ammonia a more economical alternative compared to lime due to reduced sugar loss and reduced capital cost (Jennings and Schell, 2011). On the other hand, the flashed vapour is condensed and sent to WWTP.

The pre-treated slurry is sent to a sequential hydrolysis and fermentation process in batch operation. In this process, enzymatic hydrolysis (also known as enzymatic saccharification) takes place. Cellulose fibres are broken down and converted into cellobiose, soluble gluco-oligomers, and ultimately into glucose monomers using cellulase enzymes. Cellulase enzymes include endoglucanases, exoglucanases and β-glucosidase. Endoglucanases attack the cellulose fibre to reduce the length of polymer chain; exoglucanases attack the ends of highly crystalline cellulose fibres; and β-glucosidase hydrolyses the small cellulose fragments to glucose. Since the hydrolysis process is operated at elevated temperature, higher enzyme activity and higher conversion rate of cellulose to glucose is resulted as well as smaller amount enzyme is required. According to Humbird et al. (2011), a total cellulase loading of 20 mg enzyme protein/g cellulose is required to achieve 90% conversion of glucose at a temperature of 48 ^{o}C. The yield of sugar increases with increasing load of enzyme, however, there is a significant cost implication of imported enzyme. To reduce the imported cost of enzyme, enzyme production could be implemented on-site. In order to evaluate the feasibility of an on-site production of enzyme in an integrated SBB, the economic evaluation of such a case is considered in this chapter.

Cellullase enzyme could be produced by Trichoderma asperellum and Aspergillus fumigates using sago fibres as substrate (Linggang et al., 2012). According to Linggang et al. (2012), the sago fibres obtained after hydrolysis can be used as a main carbon source for enzyme production. Since carbon is also contained in other sago biomass such as sago bark as well as the main product of sago industry, sago starch, namely, sago bark and starch could also be used for enzyme production as sago fibre. Due to this reason, the economic performance of integrated SBB using different sago biomass and completed with on-site and off-site enzymes production are evaluated to determine the most feasible option for sago industry.

After the hydrolysis process, the resulting slurry containing glucose and xylose is cooled and fermented to bioethanol. In the fermentation process, recombinant co-fermenting bacterium (Zymomonas mobilis) is used as fermenting microorganism or ethanologen. The ethanologen inoculums can be produced by mixing the slurry and nitrogen sources, i.e. Diammonium phosphate (DAP) in the fermentor. This type of fermenting microorganism can ferment glucose and xylose simultaneously to bioethanol. The minor hemicellulosic sugar arabinose is also fermented to ethanol with the same conversion as xylose, as reported in Humbird et al. (2011). Besides, some of the sugars (approximately 3%) are lost to contamination. After the fermentation process, the fermentation broth has an ethanol concentration of 5.4%. It is then sent to distillation and molecular sieve adsorption for bioethanol recovery.

In bioethanol recovery processes, water, bioethanol, and combustible solids are separated from the fermentation broth. Bioethanol with a concentration of 99.5% is obtained in the end of these processes. Firstly, fermentation broth is sent to a beer column to remove dissolved carbon dioxide and most of the water. This column is operated at approximately 2 bar overhead pressure and low reboiler temperature in order to minimise fouling problem. About 99% of ethanol vapour with an approximate concentration of 40% is produced and removed from the side of the beer column and sent to a rectification column. The condensate from the top condenser of the column is returned to the column after venting out CO_2. A small amount of ethanol is lost and is considered as permanent loss. To minimise the loss, the reboiler duty of the column needs to be kept relatively high, so there is a trade-off between ethanol loss and energy usage (Humbird et al., 2011). The bottom stream from the beer column contains unconverted insoluble and dissolved solids. This solid-rich stream is then directed to a pressure filter for dewatering. During the dewatering process, insoluble solids (lignin) with dryness 35% and filtrate are generated. Lignin is used as fuel in the CHP system, while filtrate is treated in WWTP, respectively.

In the rectification column, ethanol vapour is concentrated to a near azeotropic composition. A vapour overhead stream of 92.5% ethanol and a bottom stream of 0.05% ethanol are obtained. The overhead ethanol stream is then further dehydrated to 99.5% via a molecular sieve adsorption process. The bottom stream from the rectification column is recycled to the pretreatment process as dilution water. Water is selectively adsorbed in the adsorbent bed of the molecular sieve adsorption process and removed together with a small amount of ethanol. The pure ethanol vapour

(~99.5%) is produced and then cooled by heat exchange with the regeneration condensate from a regenerating column and then pumped to a storage tank. The low purity bioethanol generated from the regenerating column is recycled back to the rectification column to recover more bioethanol.

8.2.2 Combined Heat and Power (CHP) System

In the integrated SBB, a CHP system with biomass boiler (Configuration 1 of the CHP system presented in Chapter 7) is used to generate steam and electricity as shown in Figure 8.3. A normal pressure grate-fired biomass boiler (Huang et al., 2013), which consists of an economiser and a steam drum is used to generate high pressure (HP) superheated steam. This boiler is fed with lignin and biogas as fuel sources and air for full combustion. The boiler feed water (BFW) is pre-heated in the economiser and then turned into saturated and superheated HP steam (50 bar) in the steam drum within the boiler. Some of the resulting HP steams are sent to the SBP for bioethanol production. The remaining HP steam is sent to a back pressure turbine and a generator for electricity generation. The low pressure (LP) steam from the back pressure steam turbine is directed to the SBP to fulfil the steam requirement for bioethanol production. The balance of the LP steam can be further expanded in a condensing steam turbine and generator to generate more electricity. The generated electricity is supplied to the SBP and WWTP for self-sustenance of the integrated plant. Any excess electricity could be sent to an adjacent SSEP and sold to the grid. The generated condensate from the condensing steam turbine is recovered as BFW at ~1.0 bar and returned to the economiser via a pumping system in a closed cycle. The

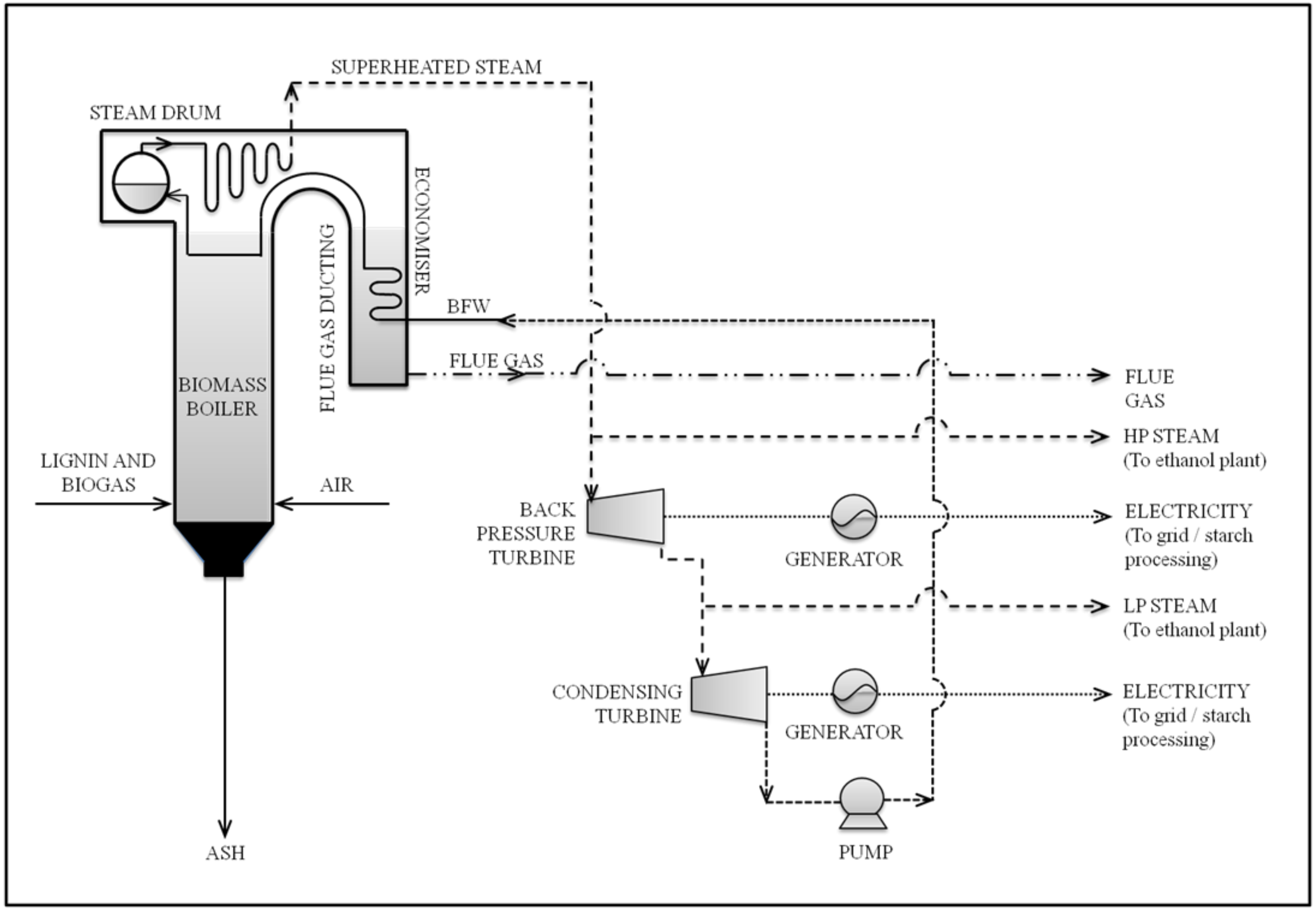

Figure 8.3: Configuration of combined heat and power (CHP) system (reproduced from Figure 7.2)

flue gas from the boiler is released to the atmosphere and the ash is collected in ash grate from the bottom of the boiler.

8.2.3 Wastewater Treatment Plant (WWTP)

Wastewater from the SBP is directed to a WWTP to produce treated water which can be reused in the SBP for bioethanol production. In this chapter, the design of the treatment process is adopted from Humbird et al. (2011). The treatment process consists of an anaerobic digester, aerobic digester, membrane bioreactor (MBR), reverse osmosis (RO) membrane unit, and sludge dewatering unit as shown in Figure 8.4. Wastewater with chemical oxygen demand (COD) of 64 g/L is first channelled to the anaerobic digester to digest organic matter in the absence of oxygen. In addition, some insoluble organic compounds in wastewater such as cellulose, xylan, and protein are present and can be removed by the pressure filter in the SBP. In the anaerobic digester, approximately 91% of each organic component is destroyed; 86% is converted to biogas containing methane that can be used as fuel in the CHP system; and 5% is converted to sludge. The production rate of methane is approximately 228 g methane/kg COD removed (Humbird et al., 2011). Sludge has a yield of 45 g sludge/kg COD digested (Humbird et al., 2011). To maintain the sludge loading in the anaerobic digester, a part of the sludge is returned to the anaerobic digester and the excess sludge is sent to a sludge holding tank. The resulting water from the anaerobic digester is pumped to the aerobic digester equipped with floating aerators that provide oxygen for aerobic digestion. In this process, removal efficiency of soluble organic matter can go up to 96% (Humbird et al., 2011). Besides, ammonium ions are also removed in this process. The existence of ammonium ions is due to the usage of ammonia in the pretreatment process of the SBP. These ions

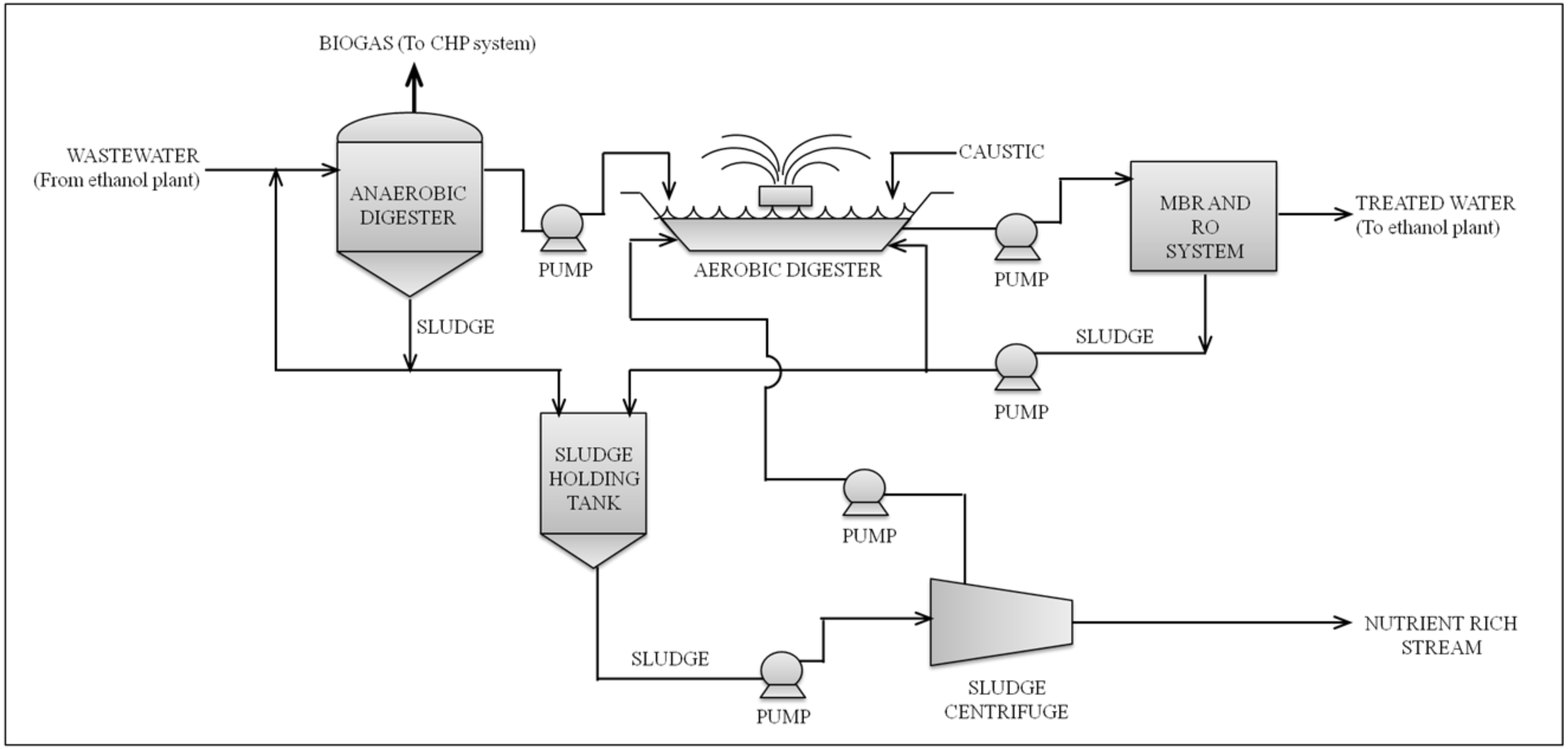

Figure 8.4: Configuration of wastewater treatment plant (WWTP)

are removed via a nitrification process by converting the ions into nitrate by nitrifying bacteria. Since nitric acid is formed in the nitrification process, pH in aerobic process is decreased. Due to this reason, caustic soda is added to the aerobic digester for neutralisation. During the aerobic process, significant amount of sludge is generated. This sludge is carried forward with the digested water to the MBR and RO system. The main purpose of these systems is to separate the sludge from digested water and clarify the water to clear treated water which can be reused or recycled. The separated sludge is mostly returned to the aerobic process to maintain the required sludge loading. The remaining sludge is pumped to the sludge holding tank and mixed with the sludge from the anaerobic process. This mixed sludge is then pumped to a centrifuge for dewatering to produce a nutrient rich stream that can be used as fertiliser or compost. The resulting water from the centrifuge is recycled to the aerobic process for additional treatment.

8.3 Methodology of Performance Evaluation for Integrated Sago-based Biorefinery (SBB)

8.3.1 Technical Performance Evaluation

The technical performance of the integrated SBB with different feedstock is first evaluated. Based on the available biomass from a sago starch processing, such as sago fibres (6.46 oven dried tonne (odt)/d), sago barks (10.20 odt/d), or combined biomass (fibres and barks, 16.66 odt/d), production yield of bioethanol and total electricity generated are determined. In order to determine the feasibility of utilisation of biomass for bioethanol production, a comparison study with bioethanol production from sago starch (12 t/d) is performed. Note that the technical performance of the integrated SBB is dependent on the production yield of bioethanol and electricity. Namely, the highest yield of bioethanol production and electricity generation leads to the highest technical performance of the integrated SBB. The integrated SBB with the highest technical performance is selected for further analysis.

In order to estimate the production yield of bioethanol and electricity of the integrated SBB, the mass composition of sago starch and sago biomass as well as the sugar contained in hydrolysed sago starch is first determined from the experiment or literature. Tables 8.1 and 8.2 show the properties of sago starch and sago biomass. Based on the properties, the production of bioethanol and electricity can be estimated via a developed spreadsheet based yield prediction model. This model is developed based on the large-scale bioethanol plant study which is conducted by NREL and reported by Humbird et al. (2011). The details of this yield model are discussed in the following section.

Table 8.1: Sago starch and biomass compositions

	Mass Composition (%, dry basis)		
	[1]Starch	[2]Fibre	[3]Bark
Starch	73.7	52.0	-
Soluble dietary fibres	3.3	-	-
Insoluble dietary fibres	4.0	-	-
Cellulose	-	16.0	23.1
Hemicellulose	-	9.8	17.3
Lignin	-	5.2	18.0
Moisture	16.1	[4]15.6	2.8
Acetate	-	[4]1.4	38.8
Ash	0.2	-	-
Protein	2.4	-	-
Lipids	0.3	-	-

Data provided by [1]Dwiarti et al. (2007); [2]Thangavelu et al. (2014); [3]University Putra Malaysia and estimated based on [4]Humbird et al. (2011) (NREL report).

In the spreadsheet based yield prediction model, mass and energy balances of the integrated SBB as well as the total amount of bioethanol produced using the available biomass feedstocks are determined based on the conversion rates, amounts

Table 8.2: Sugars contained in hydrolysed sago starch sample (Dwiarti et al., 2007)

	Mass Composition (%)
Glucose	42.8
Xylose	5.4
Cellobiose	2.3
Sucrose	1.3
Maltose	23.5
Unhydrolysed oligasacchaccharides	24.7

of required materials (e.g., sulphuric acid, HP steam, ammonia, etc.), and product ratios as applied in Humbird et al., 2011. Besides, conversion rates of hemicellulose carbohydrates (e.g., xylan, mannan, galactan and arabinan) and some glucan contained in hemicellulose side-chains to oligomers, soluble sugars (e.g., glucose, xylose, mannose, galactose and arabinose) and sugar degradation products (furfural and hydroxymethyl furfural (HMF)) as shown in Table 8.3 (in the column of pretreatment) are also used in this evaluation. As shown, the conversion rates include acetate to acetic acid and furfural and HMF to tar as well as lignin to soluble lignin.

The resulting product amounts are then inputted into the spreadsheet based yield prediction model to determine the glucose that can be produced from cellulose based on the conversion rate as shown in Table 8.3 (in the column of enzymatic hydrolysis) after reacting with either purchased or on-site produced cellulase enzyme with a feeding rate of 20 mg per gram cellulose. In the case cellulase enzyme is produced

Table 8.3: Conversion rates for pretreatment, enzymatic hydrolysis, and fermentation processes (Humbird et al., 2011)

Pretreatment		Enzymatic hydrolysis		Fermentation	
Conversion	Rate (%)	Conversion	Rate (%)	Conversion	Rate (%)
Glucan to gluco-oligomers	0.3	Cellulose to glucolig	4.0	Glucose to ethanol	95.0
Glucan to glucose	9.9	Cellulose to cellobiose	1.2	Glucose to zymo (cell mass)	2.0
Glucan to HMF	0.3	Cellulose to glucose	90.0	Glucose to glycerol	0.4
Xylan to oligomer	2.4	Cellobiose to glucose	100.0	Glucose to succinic acid	0.6
Xylan to xylose	90.0			Glucose to acetic acid	0.0
Xylan to furfural	5.0			Glucose to lactic acid	0.0
Mannan to oligomer	2.4			Xylose to ethanol	85.0
Mannan to mannose	90.0			Xylose to zymo	1.9
Mannan to HMF	5.0			Xylose to glycerol	0.3
Galactan to oligomer	2.4			Xylose to xylitol	4.6
Galactan to galactose	90.0			Xylose to succinic acid	0.9
Galactan to HMF	5.0			Xylose to acetic acid	0.0
Arabinan to oligomer	2.4			Xylose to lactic acid	0.0
Arabinan to arabinose	90.0			Arabinose to ethanol	85.0
Arabinan to furfural	5.0			Arabinose to zymo	1.9
Acetate to acetic acid	100.0			Arabinose to glycerol	0.3
Furfural to tar	100.0			Arabinose to succinic acid	1.5
HMF to tar	100.0				
Lignin to soluble lignin	5.0				

on-site, some of the hydrolysate slurries produced from the hydrolysis process rich in glucose and protein are sent to the enzyme production process. The remaining sugars in the hydrolysate slurry are then converted into ethanol and others products via the fermentation process based on the conversion rates as shown in Table 8.3 (in the column of fermentation) and the other input materials such as inoculums and DAP. The resulting streams are further used in the recovery processes. In addition, the bioethanol concentrations as discussed in Section 8.2.1 and the ratios as applied in Humbird et al. (2011) are manipulated in the developed spreadsheet based yield prediction model to determine the mass flowrates of the produced bioethanol and all other product streams (i.e., beer column, rectification column, molecular sieve adsorption column, and pressure filter). Based on the determined mass flowrates, equipment can be scaled down to estimate the required equipment size of integrated SBB. Although the scale of integrated SBB is smaller than the NREL's process design, the choice and performance of scaled down equipment are assumed same as the NREL's study.

On the other hand, the resulting lignin and filtrate from the pressure filter are sent to the CHP system and WWTP for CHP and biogas generation, respectively. Note that the amount of generated biogas is determined based on the removal efficiency of chemical oxygen demand (COD) (91%) and biogas production rate (228 g methane/kg COD removed) (Humbird et al., 2011). In this chapter, approximately 64 g/l of total COD is entered the anaerobic digester. The generated biogas is then fed into a CHP system (as described in Section 8.2.2) with lignin and then utilised as fuel sources in the biomass boiler for heat and power generation. Note that the proposed CHP system is deviated from the process given in Humbird et al. (2011).

This proposed CHP system is adapted from Chapter 7. In order to determine the potential of heat and power generation from the CHP system; the boiler efficiency (η^{Boiler}) of 80% is set in this chapter (Thornley et al., 2009). Next, the extractable energy from the biomass boiler can be determined theoretically based on the calorific values of lignin (11.14 kJ/g) (Humbird et al., 2011) and biogas (12.54 kJ/g) (Humbird et al., 2011) as shown in Equation (8.1).

$$\text{E}^{\text{Out}} = \sum_{k} \text{M}_{k}^{\text{In}} \text{E}_{k}^{\text{In}} \eta^{\text{Boiler}} \tag{8.1}$$

where E^{Out} is the total extractable energy from the biomass boiler; E_{k}^{In} and M_{k}^{In} are the calorific value and the intake of dried biomass *k* fed into the boiler, respectively. Based on the extractable energy, the total mass flow rate of steam generation, m_{steam} can be determined theoretically via Equation (8.2) (Sadhukhan et al., 2014):

$$\text{E}^{\text{Out}} = m_{steam} \left[\text{C}_{\text{p}} \left(\text{T}_{\text{sat}} - \text{T}_{\text{BFW}} \right) + \Delta \text{h}_{\text{vap}} + \left(\text{h}_{\text{sup}} - \text{h}_{\text{v}} \right) \right] \tag{8.2}$$

where C_{p} is the heat capacity of water. Meanwhile, $\Delta\text{h}_{\text{vap}}$, h_{v} and h_{sup} are the enthalpy of vaporisation of water, specific enthalpies of saturated steam and superheated steam, respectively. In this process, the steam generation is determined based on the following operating conditions.

- Pressure of the HP superheated steam = 50 bar.
- Temperature of the HP superheated steam = 500 $^{\text{o}}$C.

Table 8.4: Utility consumptions of sago-based bioethanol plant (SBP) (on-site enzyme production)

	Starch			**Fibre**		
Process unit	Process water (kg/d)	Electricity (kW)	Steam (kg/d)	Process water (kg/d)	Electricity (kW)	Steam (kg/d)
Feedstock handling	-	4.95	-	-	2.66	-
Pretreatment	82,685	32.72	3456 (HP)	40,290	17.61	1728 (HP)
Hydrolysis and fermentation	-	15.18	-	-	8.17	-
Enzyme production	86	30.76	-	378	16.55	-
Recovery	-	12.23	15,552 (LP)	-	6.58	7776 (LP)
Total	82,771	95.84	19,008	40,668	51.57	9,504

	Bark			**Fibre + bark**		
Process unit	Process water (kg/d)	Electricity (kW)	Steam (kg/d)	Process water (kg/d)	Electricity (kW)	Steam (kg/d)
Feedstock handling	-	4.21	-	-	6.87	-
Pretreatment	73,475	27.81	3456 (HP)	96,215	45.42	5184 (HP)
Hydrolysis and fermentation	-	12.91	-	-	21.08	-
Enzyme production	882	26.15	-	1260	42.70	-
Recovery	-	10.40	10,368 (LP)	-	16.99	19,008 (LP)
Total	74,357	81.48	13,824	97,475	133.06	24,192

Table 8.5: Utility consumptions of sago-based bioethanol plant (SBP) (off-site enzyme production)

Process unit	Starch			Fibre		
	Process water (kg/d)	Electricity (kW)	Steam (kg/d)	Process water (kg/d)	Electricity (kW)	Steam (kg/d)
Feedstock handling	-	4.95	-	-	2.66	-
Pretreatment	81,523	32.72	3456 (HP)	41,514	17.61	1728 (HP)
Hydrolysis and fermentation	-	15.18	-	-	8.17	-
Enzyme production	-	-	-	-	-	-
Recovery	-	12.23	16,416 (LP)	-	6.58	8640 (LP)
Total	81,523	65.08	19,872	41,514	35.02	10,368

Process unit	Bark			Fibre + Bark		
	Process water (kg/d)	Electricity (kW)	Steam (kg/d)	Process water (kg/d)	Electricity (kW)	Steam (kg/d)
Feedstock handling	-	4.21	-	-	6.87	-
Pretreatment	54,376	27.81	3456 (HP)	96,553	45.42	5184 (HP)
Hydrolysis and fermentation	-	12.91	-	-	21.08	-
Enzyme production	-	-	-	-	-	-
Recovery	-	10.40	11,232 (LP)	-	16.99	19,008 (LP)
Total	54,376	55.33	14,688	96,553	90.36	24,192

- Saturation temperature of steam, T_{sat}, at 50 bar = 264^{o}C .
- Temperature of BFW, T_{BFW} = 105 ^{o}C .

The steam requirement by the SBP as shown in Tables 8.4 and 8.5 is supplied to the processes. The remaining steam is then used for power generation via the back pressure and condensate steam turbines. These unit operations are simulated using commercial software, Aspen Plus V7.1, which is a standard process simulation tool and has been widely adopted to simulate biomass CHP systems (Huang et al., 2013; Ng and Sadhukhan, 2011a,b), to determine the total power generated from the CHP system with following operating conditions.

- Discharge pressure of back pressure steam turbine = 5 bar.
- Discharge pressure of condensate steam turbine = 1.0 bar.

Apart from the steam, other utilities such as electricity as shown in Tables 8.4 and 8.5 are also required in SBP to produce bioethanol regardless the enzyme production is on-site or off-site. Based on these data, electricity to grid can be determined by deducting the total usage of electricity in SBP and WWTP from the total generated electricity. Based on the estimated amount of bioethanol produced and electricity generated from the integrated SBB, the integrated SBB with the highest technical performance is selected as the most feasible case for further evaluation.

8.3.2 Environmental Performance Evaluation

In this chapter, the environmental performance of integrated SBB is evaluated based on the reduction in carbon dioxide (CO_2) emission only. This is because the main products of the integrated SBB i.e., bioethanol and energy can replace gasoline and grid electricity respectively, and thereby reduce CO_2 emission to the atmosphere. Based on the abovementioned assumptions, the reduced CO_2 can be determined using Equation (8.3).

$$
\begin{aligned}
CFP_{m'}^{\mathrm{SBB\_Reduced}} &= \left(ELEC_{m'}^{\mathrm{SBB\_Generated}} \times \mathrm{OPHR}_{m'}^{\mathrm{SBB}} \times \mathrm{EF}^{\mathrm{Grid}}\right) \\
&+ \left(BETH_{m'}^{\mathrm{SBB\_Generated}} \times \mathrm{CF}^{\mathrm{L\_TON}} \times \mathrm{LHV}^{\mathrm{ETHANOL}} \times \mathrm{EF}^{\mathrm{GF}}\right) \qquad \forall\, m' \qquad (8.3)
\end{aligned}
$$

where $CFP_{m'}^{\mathrm{SBB\_Reduced}}$ (kg CO_2/d) is the total reduced CO_2 of integrated SBB with biomass/starch *m'* for bioethanol production. $ELEC_{m'}^{SBB\_Generated}$ (kW) and $\mathrm{OPHR}_{m'}^{\mathrm{SBB}}$ (h/d) are referred to the electricity generated, and operational hours of integrated SBB with biomass/starch *m'*, respectively, while $\mathrm{EF}^{\mathrm{Grid}}$ (kg CO_2/kWh) is the carbon emission factor of grid electricity generated from fossil fuel in Sarawak, Malaysia. As mentioned in Chapter 4, the grid electricity in Sarawak is a combined power from different power plants (i.e., combined cycle, coal-fired, hydro, gas-turbine, and diesoline power plant) and supplied to most of the industry in Sarawak (SEB, 2010). Hence, in this chapter, the carbon emission factor of the grid electricity at Sarawak, Malaysia is taken as 0.8990 kg CO2/kWh (determined in Chapter 4) with 20 hours of operating basis. Meanwhile, $BETH_{m'}^{\mathrm{SBB\_Generated}}$, $\mathrm{CF}^{\mathrm{L\_TON}}$, $\mathrm{LHV}^{\mathrm{ETHANOL}}$, $\mathrm{EF}^{\mathrm{GF}}$ are the bioethanol production in integrated SBB with biomass/starch *m'* (t/d), conversion factor of bioethanol volume from tonne to litre, lower heating value of bioethanol (MJ/l), and well-to-wheels emission factor of gasoline use as transportation fuel (kg CO_2 equivalent/MJ), respectively. $\mathrm{CF}^{\mathrm{L\_TON}}$ and $\mathrm{LHV}^{\mathrm{ETHANOL}}$ are given as 1262 l/t and 21.1 MJ/l, respectively (Bioenergy Feedstock Information Network, 2014);

while, 0.086 kg CO_2 equivalent / MJ of EF^{GF} is used in this chapter. Note that this well-to-wheel emission factor is extracted from the GREET model, Version 2014, developed by Argonne National Laboratory.

8.3.3 Economic Performance Evaluation

Similar to Chapter 7, in order to investigate the viability of integrated SBB utilising different biomass feedstocks for bioethanol production, the economic evaluation is performed by adopting the economic analysis methodology as presented in Sadhukhan et al. (2014). According to Sadhukhan et al. (2014), a list of equipment for the integrated SBB is first to be compiled. Since this is a preliminary analysis for sago industry, the sizes of the equipment are estimated based on the developed spreadsheet based yield prediction model and Aspen Plus simulation model. Then, by applying the concept of economy of scale, the base cost of equipment with a specific size adopted from Humbird et al. (2011) and Sadhukhan et al. (2014) is scaled down to obtain the cost of equipment for the given plant size via Equation (8.4):

$$\frac{COST_{SIZE2}}{\mathrm{COST}_{SIZE1}} = \left(\frac{\mathrm{SIZE}_2}{\mathrm{SIZE}_1}\right)^{\mathrm{R}} \tag{8.4}$$

where SIZE_1 and SIZE_2 is the capacity of the base system and the capacity of the system after scaling down, respectively. COST_{SIZE1} is the cost of the base system and $COST_{SIZE2}$ is the cost of the system after scaling down; R is the scaling factor which can be taken from Humbird et al. (2011) and Sadhukhan et al. (2014). Note that different R factors are used for different types of equipment. To update the cost of equipment from their given base years, Equation (8.5) and the Chemical Engineering Plant Cost Index of year 2014 (574.4) are used in this chapter.

$$C_{pr} = \mathrm{C}_o \times \left(\frac{\mathrm{I}_{pr}}{\mathrm{I}_o} \right) \tag{8.5}$$

where C_{pr} is the present cost, $\mathrm{C_o}$ is the original cost, I_{pr} is the present index value, and I_o is the original index value. Note that, the original index value of equipment maybe different from each other as it is dependent on the given base year of the equipment. Then, Guthrie's method is applied to determine the total capital investment (TCI) using installation factors of individual unit operations obtained from Humbird et al. (2011) and Sadhukhan et al. (2014). In order to estimate the equipment cost, the concept of economy of scale is used in this chapter. Note that, the investment or infrastructural cost for process integration is included in the total capital investment cost.

Next, the annual operating cost is determined, which is the summation of the fixed and variable operating costs. The fixed operating cost includes the costs of maintenance, personnel, laboratory, supervision, plant overheads, capital charges, insurance, local taxes, royalties, sale expense, general overheads and research and development (Sadhukhan et al., 2014). These costs are determined based on the labour cost and indirect capital cost. Since the SBP is integrated with the existing SSEP, some of the existing staff in the SSEP can be allocated to the SBP and hence only one additional worker per shift can be employed. In this case, labour cost need to be considered in the SBP, which is taken as hire new labour (HL) in this chapter. In contrast, if the SSEP provides all manpower to the SBP, labour cost can be excluded from the SBP, which is known as use current available labour (UCL). Besides, in order to determine the indirect capital cost, the Lang's method is used.

The variable operating cost is the total of the raw material cost, utilities cost and transportation cost. Sago starch and sago biomass are supplied by the SSEP without any charges. For other raw materials, their unit costs are as shown in Table 8.6. Note that the cellulase enzyme cost is not accounted for the SBP case with on-site enzyme production. In the case the enzyme is purchased from suppliers (off-site enzyme production), a unit cost of enzyme is applied, as shown in Table 8.6. In addition, a unit cost of fresh water as shown in Table 8.6 is used to determine the utility cost. The average transportation cost of biomass feedstock is assumed at \$0.60/GJ (Sadhukhan et al. 2014). To determine the revenue, an electricity price of \$0.1375/kWh (8.03 p/kWh) (Department of Energy & Climate Change, 2014) and an ethanol price of \$0.92/kg (Sadhukhan et al., 2008) are used. Based on these data, the profit and payback period of integrated SBB with different feedstock is determined.

Table 8.6: Unit prices of products, raw materials and utilities

	Unit price (USD/kg)
Products	
[1]Ethanol	0.9204
Raw materials	
[2]Sulfuric acid (H_2SO_4), 93%	0.0880
[2]Ammonia (NH_3)	0.4394
[2]Diammonium phosphate (DAP)	0.9667
[1]Cellulase enzyme	3.1200
[2]Caustic	0.1495
[2]Lime	0.1993
[2]Boiler chemicals	4.9959
[2]Cooling tower chemicals	2.9939
Utilities	
[2]Fresh water	0.0002
[3]Electricity	0.1375 (USD/kWh)

Data extracted from [1]Sadhukhan et al. (2008); [2]Humbird et al. (2011); and [3]Department of Energy & Climate Change.

8.4 Results and Discussion

8.4.1 Technical Performance of Integrated Sago-based Biorefinery (SBB)

The technical performance of the integrated SBB with different biomass/starch, with on-site and off-site enzyme production, is presented in Tables 8.7 and 8.8, respectively.

As shown in Table 8.7, the integrated SBB with on-site enzyme production and using combined biomass (fibre + bark) as feedstock has the highest amount of bioethanol production (4.75 t/d). This is followed by sago starch (4.17 t/d of bioethanol), barks (2.75 t/d of bioethanol), and fibres (2.01 t/d of bioethanol). However, combined biomass gives lower bioethanol production yield (0.28 t of bioethanol/t of biomass) compared to sago starch (0.35 t of bioethanol/t of biomass) as shown in Table 8.7. These results are reasonable as there is higher sugar content in sago starch compared to sago biomass (Singhal et al., 2008). On the other hand, it is noted that the integrated SBB using combined biomass produces the highest amount of electricity (252 kW/d) (see Table 8.7).

Table 8.8 shows the technical performance of the integrated SBB with off-site enzyme production. This technical performance has similar trend to the integrated SBB with on-site enzyme production as shown in Table 8.7. The integrated SBB using combined biomass as fuel source achieves the highest production of bioethanol (5.23 t/d) and this is followed by sago starch (4.28 t/d), barks (2.95 t/d), and fibres (2.26 t/d). However, similar with on-site enzyme production (Table 8.7), combined biomass has lower bioethanol production yield (0.31 t of bioethanol/t of biomass)

Table 8.7: Technical and environmental performance of integrated sago-based biorefinery (SBB) (on-site enzyme production)

Scenarios	Starch	Fibres	Barks	Fibre + bark
Calorific value (kJ/g)	NA	14.20	19.30	17.30
Raw materials (t/d , dry basis)	12.00	6.46	10.20	16.66
Produced bioethanol (t/d)	4.17	2.01	2.75	4.75
Production yield of bioethanol (t of bioethanol/t of biomass)	0.35	0.31	0.27	0.28
Generated lignin to CHP system (t/d)	6.34	3.22	4.14	7.65
Generated biogas (t/d)	3.72	1.86	2.44	4.40
Generated energy (kW/d)	1303.00	657.00	852.00	1559.00
Total generated VHP steam (kg/d)	35,424.00	19,008.00	25,056.00	45,792.00
Required LP steam (kg/d)	15,552.00	7776.00	10,368.00	19,008.00
Required HP steam (kg/d)	3456.00	1728.00	3456.00	5184.00
Generated electricity (kW/d)	217.00	116.63	136.40	252.00
Eff. of electricity generation (%)	14.00	14.00	14.00	14.00
Electricity consumption (kW/d)	156.43	84.18	133.00	217.19
- Ethanol production	95.84	51.57	81.48	133.06
- WWTP	42.44	22.84	36.08	58.92
- Storage and utilities	18.15	9.77	15.44	25.21
Electricity consumption / ethanol produced (kW/t d)	23.00	25.70	29.68	28.15
Electricity to grid (kW/d)	60.56	32.44	3.40	35.30
Total required water (t/d)	82.28	40.67	74.36	97.48
Make up water (t/d)	18.75	8.72	16.39	21.75
Reduced carbon dioxide (kgCO_2 equivalent/d)	14,234.00	7,114.00	9,229.00	16,315.00

Table 8.8: Technical and environmental performance of integrated sago-based biorefinery (SBB) (off-site enzyme production)

Scenarios	Starch	Fibres	Barks	Fibre + bark
Calorific value (kJ/g)	NA	14.20	19.30	17.30
Raw materials (t/d , dry basis)	12.00	6.46	10.20	16.66
Produced bioethanol (t/d)	4.28	2.26	2.95	5.23
Production yield of bioethanol (t of bioethanol/t of biomass)	0.36	0.35	0.29	0.31
Generated lignin to CHP system (t/d)	6.51	3.43	4.47	7.93
Generated biogas (t/d)	3.8	1.97	2.56	4.56
Generated energy (kW/d)	1337.00	699.64	910.00	1617.00
Total generated VHP steam (kg/d)	38,880.00	20,736.00	26,784.00	47,520.00
Required LP steam (kg/d)	16,416.00	8640.00	11,232.00	19,008.00
Required HP steam (kg/d)	3456.00	1728.00	3456.00	5184.00
Generated electricity (kW/d)	233.21	120.60	148.97	275.60
Eff. of electricity generation (%)	14.00	14.00	14.00	14.00
Electricity consumption (kW/d)	125.68	67.64	106.85	174.49
- Ethanol production	65.08	35.05	55.33	90.36
- WWTP	42.44	22.84	36.08	58.92
- Storage and utilities	18.16	9.77	15.44	25.21
Electricity consumption / ethanol produced (kW/t d)	15.16	15.53	18.78	17.27
Electricity to grid (kW/d)	107.53	52.96	42.12	101.11
Total required water (t/d)	81.52	41.51	54.38	96.55
Make up water (t/d)	15.86	7.54	10.33	18.09
Reduced carbon dioxide ($kgCO_2$ equivalent/d)	14,840.00	7,771.00	9,960.00	17,927.00

compared to sago starch (0.36 t of bioethanol/t of biomass). On the other hand, highest amount of electricity (275.6 kW/d) can be generated from the integrated SBB that is using combined biomass as fuel source.

As shown in Tables 8.7 and 8.8, the production yield of bioethanol from sago fibres is found 0.31 t of bioethanol/t of biomass and 0.35 t of bioethanol/t of biomass for the integrated SBB with on-site and off-site enzyme production, respectively. It is interesting to note that these results are close to the expected theoretical ethanol yield from sago fibres (0.38 t of bioethanol/t of fibres) as reported in Thangavelu et al. (2014). Note that approximately 60% of the fibres are starch (Singhal et al., 2008) and hence fibres always have higher production yield amongst the sago biomass. Besides, it is also found that more bioethanol is produced from the integrated SBB with off-site enzyme production. This is because a higher amount of hydrolysate slurry is sent to the fermentation process compared to the integrated SBB completed with on-site enzyme production, where some of the hydrolysate slurry was used in enzyme production. On the other hand, the integrated SBB with off-site enzyme production has higher electricity generation for export through grid, compared to the integrated SBB completed with on-site enzyme production. This is due to the additional electricity consumption in the enzyme production.

As an overall observation from the technical performance evaluation of the integrated SBB, the integrated SBB with combined biomass has the highest production yield of bioethanol and electricity. Besides, combined biomass also generates the highest amount of lignin, biogas, total energy including HP steam and electricity, compared to sago starch, fibres and barks individual performance.

Therefore, it is selected for further analysis. Tables 8.9 and 8.10 show the mass flowrates of all resulting streams in the SBP extracted from the model.

8.4.2 Environmental Performance of Integrated Sago-based Biorefinery (SBB)

In addition to the technical performance analysis, Tables 8.7 and 8.8 also show the environmental performance of the integrated SBB with on-site and off-site enzyme production, respectively. As shown in Table 8.7, the integrated SBB using combined biomass as fuel source has the highest environmental performance as it has the largest CO_2 emission reduction potential, (~16.32 tCO_2 equivalent/d). This is followed by sago starch (~14.23 tCO_2 equivalent/d), sago barks (~9.23 tCO_2 equivalent/d), and sago fibres (~7.11 tCO_2 equivalent/d). In the same order, about 17.93 tCO_2 equivalent/d, 14.84 tCO_2 equivalent/d, 9.96 tCO_2 equivalent/d, and 7.77 tCO_2 equivalent/d of CO_2 are reduced, respectively, for the integrated SBB with off-site enzyme production (Table 8.8). Similarly with the technical performance evaluation results (Tables 8.7 and 8.8), combined biomass has the largest reduction potential of CO_2 due to its highest yield of electricity generation and bioethanol production.

8.4.3 Economic Performance of Integrated Sago-based Biorefinery (SBB)

As mentioned previously, utilisation of sago starch as feedstock for bioethanol production is not the intention of this chapter as it is one of the important foods for human. However, it is used for comparison against the performance of sago biomass. Hence, detailed economic evaluation is only focusing on sago biomass. To simplify

Table 8.9: Mass streams of sago-based bioethanol plant (SBP) (on-site enzyme production)

Streams (kg/d, dry basis)	On-site enzyme production			
	Starch	Fibre	Bark	Fibre + bark
Pretreatment				
Biomass	12,000	6458	10,202	16,660
Process water	82,685	40,289	73,476	77,215
Sulfuric acid	228	123	194	317
Ammonia	123	67	121	183
Hydrolysis and fermentation				
Pretreatment slurry	50,336	28,163	51,347	79,506
Cellulase enzyme	105	458	1068	1527
Hydrolysate slurry	49,591	23,621	48,315	75,933
DAP	16	8	16	25
CSL	126	59	121	190
Inoculum	4919	2343	4792	7532
Ethanol recovery				
Beer	78,186	39,725	51,018	94,809
Ethanol vapour (beer column)	10,170	5167	6636	12,522
Beer stillage	67,911	34,504	44,313	81,938
Vent	105	55	69	350
Ethanol vapour (rectification column)	5476	3218	3597	6461
Ethanol / water	1285	1200	838	1711
Dehydrated ethanol	4192	2018	2759	4750
Enzyme production				
Hydrolysate slurry (to enzyme production)	850	5000	4100	5100
Pressure filter				
Lignin (to CHP system)	6338	3220	4136	7647
Filtrate (to WWTP)	61,583	31,290	40,184	74,303

Table 8.10: Mass streams of sago-based bioethanol plant (SBP) (off-site enzyme production)

Streams (kg/d, dry basis)	Off-site enzyme production			
	Starch	Fibre	Bark	Fibre + bark
Pretreatment				
Biomass	12,000	6458	10,202	16,660
Process water	81,523	41,514	50,139	76,966
Sulfuric acid	228	123	194	317
Ammonia	123	67	121	183
Hydrolysis and fermentation				
Pretreatment slurry	50,333	28,181	51,755	79,498
Cellulase enzyme	104	458	1068	1527
Hydrolysate slurry	50,438	28,639	52,823	81,025
DAP	17	9	17	26
CSL	126	71	130	199
Inoculum	4993	2795	5134	7885
Ethanol recovery				
Beer	80,278	42,296	55,160	98,109
Ethanol vapour (beer column)	10,442	5502	7175	12,774
Beer stillage	69,728	36,737	47,910	84,967
Vent	109	57	75	369
Ethanol vapour (rectification column)	5623	2963	3867	6729
Ethanol / water	1319	695	906	1469
Dehydrated ethanol	4304	2268	2960	5260
Pressure filter				
Lignin (to CHP system)	6508	3429	4471	7930
Filtrate (to WWTP)	63,231	33,315	43,447	77,050

the economic analysis, only the integrated SBB with payback period less than 30 years are summarised and shown in Figure 8.5. In others words, the payback period of the others scenarios, which are not shown in Figure 8.5, is more than 30 years. As shown in Figure 8.5, for the integrated SBB with off-site enzyme production (purchase enzyme), sago starch is the only feedstock that has a payback period of less than 30 years for bioethanol production. In contrast, for the integrated SBB with on-site enzyme production, all the integrated SBB which is using sago biomass as feedstock including sago starch are projected positive outcome (less than 30 years of payback period). As shown in Figure 8.5, the payback period is highly dependent on labour cost. Note that the main purpose of comparing the results of hire new labour (HL) and use current available labour (UCL) is to demonstrate the importance and impact of labour cost on the economic evaluation. As shown in Figure 8.5, in case where new labour is hired or the labour cost is included, the payback period is doubled for the integrated SBB using sago starch and combined biomass, and more than 30 years for the integrated SBB using sago fibres or barks as feedstock. Since, the combined biomass has the lower payback period (6.6 years) and the highest technical performance amongst the sago biomass, it is chosen for further detailed economic analysis. Its detailed economic performance as feedstock for bioethanol and electricity production is shown in Table 8.11. Based on the results above (Figure 8.5 and Table 8.11), it is noted that both enzyme and labour costs are the critical cost contributors to pay due attention for the development of new integrated SBB as both costs give significant impact to payback period. Therefore, a sensitivity analysis on the payback period of integrated SBB is conducted due to variations in enzyme and labour costs.

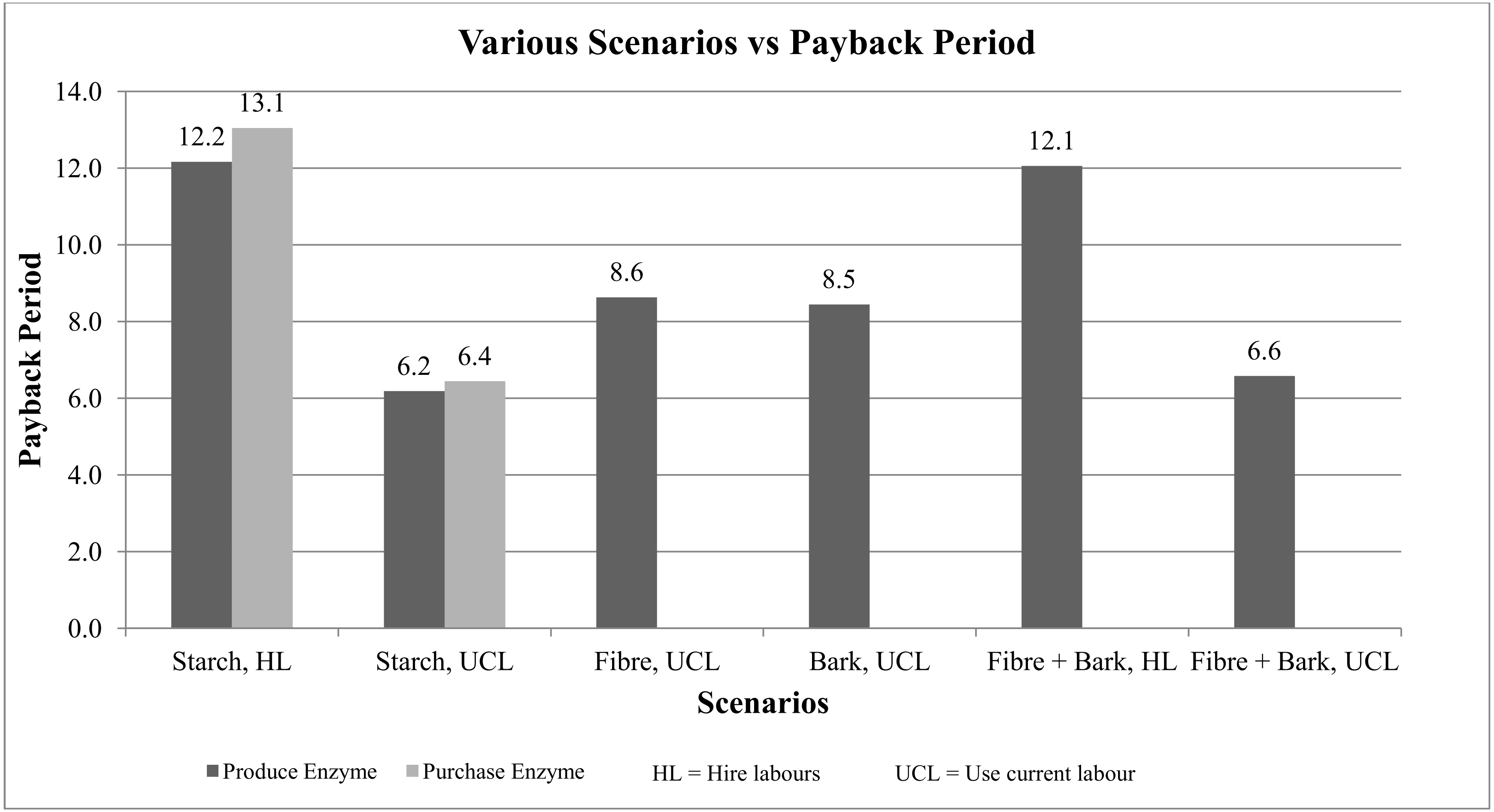

Figure 8.5: Payback period of various scenarios

Table 8.11: Economic performance of integrated sago-based biorefinery (SBB)

	Off-site enzyme production		On-site enzyme production	
Raw material	Fibre + bark		Fibre + bark	
Scenario	c/w Labour	w/o Labour	c/w Labour	w/o Labour
Total capital cost (million $)	7.118	7.118	6.929	6.929
Feedstock handling (million $)	0.580	0.580	0.580	0.580
Pretreatment (million $)	1.310	1.310	1.310	1.310
Hydrolysis and fermentation (million $)	0.776	0.776	0.733	0.733
Cellulase enzyme production (million $)	-	-	0.021	0.021
Cellulase enzyme purchase (million $/y)	1.238	1.238	-	-
Ethanol recovery (distillation) (million $)	0.810	0.810	0.769	0.769
WWTP (million $)	1.471	1.471	1.412	1.412
Storage System (million $)	0.242	0.242	0.230	0.230
Utilities system (million $)	0.368	0.368	0.368	0.368
CHP system (million $)	1.561	1.561	1.506	1.506
Total Operating Cost (million $/y)	**2.149**	**1.671**	**0.601**	**0.122**
Revenue (million $/y)	**1.370**	**1.370**	**1.175**	**1.175**
Profit (million $/y)	**(0.779)**	**(0.301)**	**0.574**	**1.053**
Payback Period (y)	**Not Feasible**	**Not Feasible**	**12.06**	**6.58**

8.5 Sensitivity Analysis for Different Scenarios

Based on the results of economic performance evaluation (see Table 8.11 and Figure 8.5), it is noted that an enzyme cost of USD 3.12 /kg taken from Sadhukhan et al. (2008) gave infeasible payback period to integrated SBB. Therefore, a lower range of enzyme cost (USD 1.0 – 3.12 / kg) is set in this sensitivity analysis to examine its impact on the payback period. Noted that USD 1.0 / kg is the lowest selling price of enzyme in current market. In addition, a range of labour cost (USD 0 – 30 / h / person of labour) is also used in this analysis. The first base case is given to analyse the payback period of the integrated SBB using combined biomass and with off-site enzyme production (purchase enzyme). The results are summarised and shown in Figure 8.6. Note that only the scenarios with feasible payback periods (less than 30 years) are shown in Figure 8.6.

As shown in Figure 8.6, when no new hiring labour is needed (USD 0 / h / person), to maintain the feasible payback period (< 30 years), the maximum enzyme cost is USD 2.0 / kg. When the enzyme is purchased at a cost higher than USD 2.0 / kg, the economic performance of the system will be infeasible. Meanwhile, when the labour cost goes up to USD 5 / h / person, USD 10 / h / person, and USD 15 / h / person, the maximum enzyme cost is decreased to USD 1.8 / kg, USD 1.7 / kg, and USD 1.5 / kg, respectively. Note that the maximum enzyme cost is further decreased to USD 1.3 / kg, USD 1.2 / kg, and USD 1.0 / kg if the labour cost increases to USD 20 / h / person, USD 25 / h / person, and USD 30 / h / person, respectively.

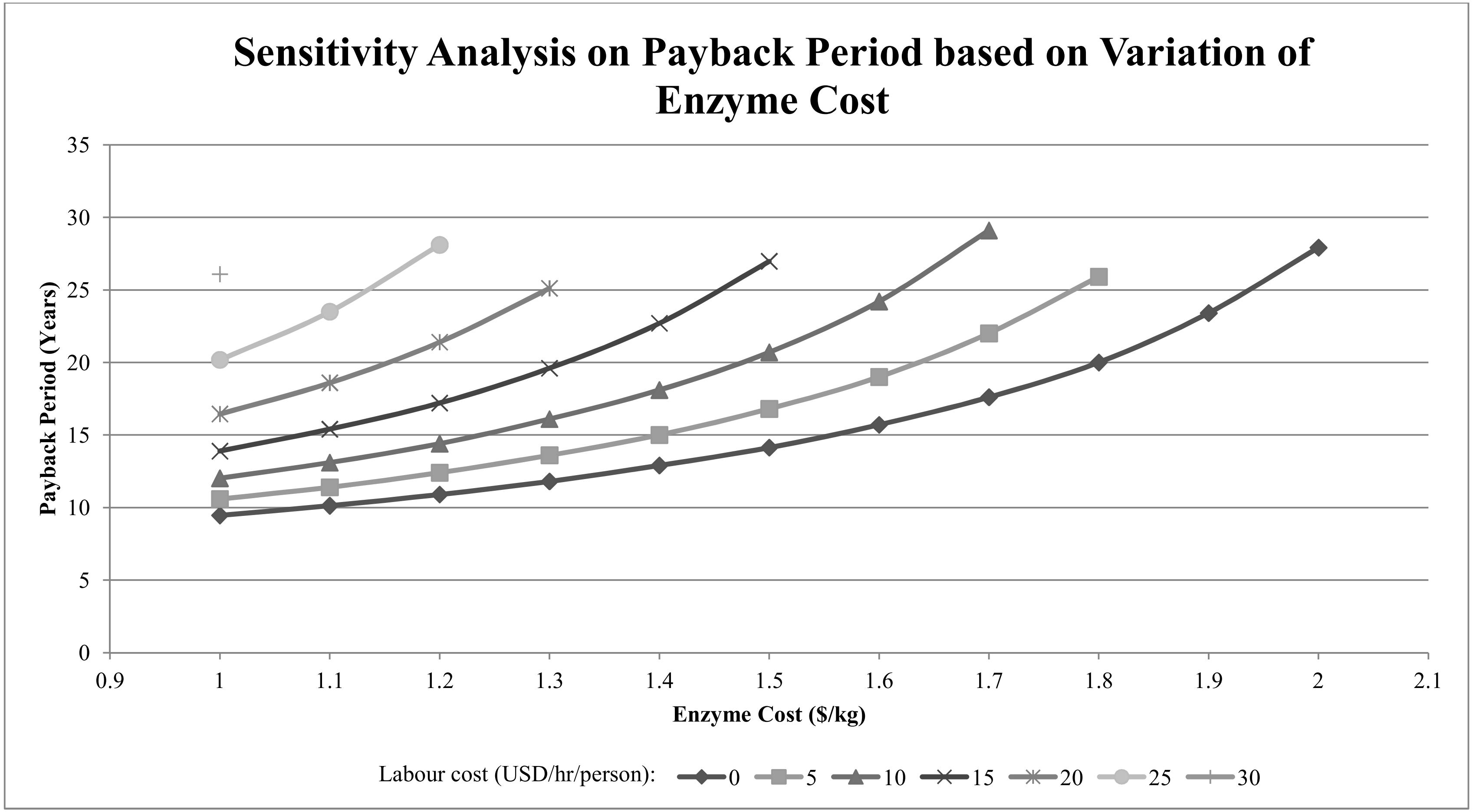

Figure 8.6: Sensitivity analysis on payback period based on variation of enzyme cost (off-site production)

For the second base case, the integrated SBB with combined biomass as feedstock and completed with on-site enzyme production is further analysed. Since the enzyme is produced on-site, no external enzyme is needed. Therefore, only sensitivity analysis on labour cost (USD 0 – 30 / h / person) is performed and the result is shown in Figure 8.7. As shown, the lowest payback period is ~6.6 years when no new labour is needed. Note that the payback period is increased proportionally with labour cost. When the labour cost increases to USD 30 / h / person, the payback period increases to 12 years (see Figure 8.7). Besides, it is also noted that to achieve a payback period less than 10 years, the labour cost should be lower than USD 20 / h / person.

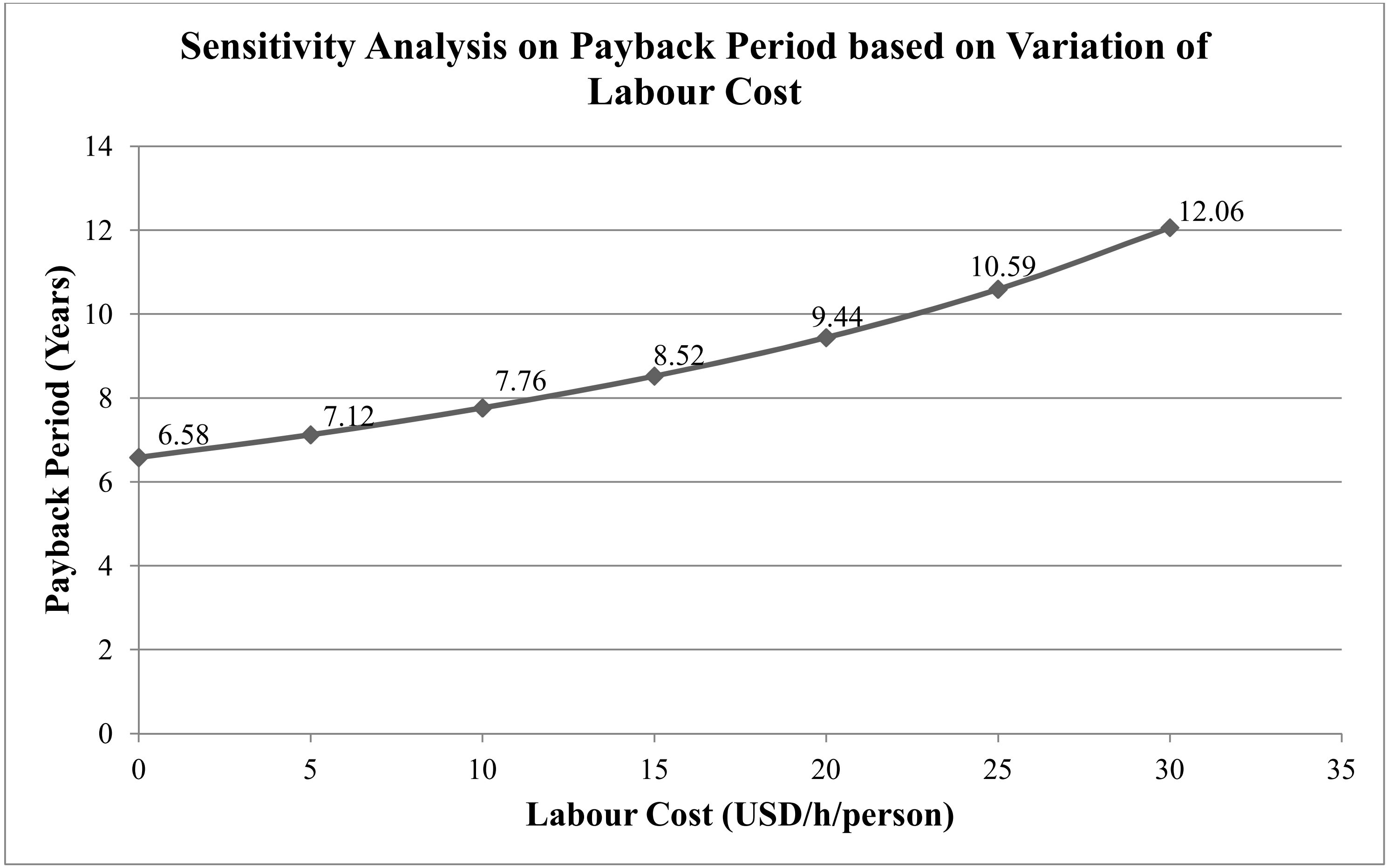

Figure 8.7: Sensitivity analysis on payback period based on variation of labour cost (on-site enzyme production)

8.6 Summary

In this chapter, techno-economic analysis to examine the feasibility of an integrated bioethanol production and energy systems is conducted. A conceptual integrated sago-based biorefinery (SBB) has been envisioned and analysed for integration with existing sago starch extraction process. The first detailed techno-economic and environmental performance analyses of sago biomass utilisation for bioethanol production in integrated SBB are presented in this chapter. Integrated SBB with different types of biomass as feedstock, with on-site and off-site enzyme production has been analysed. Based on the process simulation and the developed spreadsheet-based yield prediction models, detailed techno-economic and environmental analyses were performed to arrive following conclusions:

(1) Apart from sago starch, combined biomass (fibres + barks) has the highest technical, economic, and environmental performance compared to individual usages of sago fibre and barks in integrated SBB.

(2) Approximately 37.7 t/d of wastes on wet basis (20.8 t/d of sago barks; 16.9 t/d of sago fibres) and 16.32 – 17.93 tCO_2 equivalent/d of CO_2 could be reduced when combined biomass is used as feedstock in SBP.

(3) By using combined biomass in the integrated SBB with on-site enzyme production and making use of existing man power from the existing SSEP its economic performance can be improved (6.6 years of payback period).

(4) Enzyme and labour costs are critical cost contributors in the economics of the integrated SBB. Hence, an on-site enzyme production is vital to be implemented in bioethanol plant to achieve a higher economic performance.

(5) Process integration as shown in Figures 8.1– 8.4 is important to implement in a new development of sago-based biorefinery in order to achieve higher economic performance. In case the sago-based bioethanol plant is stand-alone, the costs of biomass and utilities are expected to increase and leading to infeasibility of the bioethanol plant.

In order to encourage the owners of SSEP, WWTP, CHP system, and SBP to form an integrated SBB for sago industry, deserve benefits of each owner participated in integrated SBB is vital to be allocated. Therefore, cooperative game theory is adopted in next chapter for allocation of benefits in integrated SBB.

CHAPTER 9

AN OPTIMISATION-BASED COOPERATIVE GAME APPROACH FOR SYSTEMATIC ALLOCATION OF COSTS AND BENEFITS IN INTERPLANT PROCESS INTEGRATION

9.1 Introduction

In this chapter, an approach based on cooperative game theory which involves pooling the benefits is proposed and then subsequently developed a rational and defensible scheme for sharing the incremental benefits among the partners. The approach is a linear programming (LP) cooperative game model. Such approach is able to allocate the benefits that accrue from interplant integration in an eco-industrial park (EIP) which use geographic clustering to promote sustainable exchange of materials and energy streams among different plants and companies. A literature case study is first solved to demonstrate the approach, and the results are compared with those determined via alternative cooperative game techniques. Then, an industrial case study on interplant integration in integrated sago-based biorefinery (SBB) is solved to further illustrate the applicability of this technique.

9.2 Problem Statement

The formal problem statement for the cooperative game approach to benefits sharing in an EIP is as follows.

- Given ℵ as the set of all companies/plants from a coalition S which can be formed by company/plant d. Each coalition thus represents a possible cluster of plants that will be involved in interplant integration.
- The characteristics function value $v(S)$ can be referred as the summation of all payoffs of companies/plants x_d in the coalition; this payoff represents the joint benefits (i.e., savings) arising from the partnership. For instance, if there are three companies (d_1, d_2 and d_2) that are interested to form a coalition, the characteristic function value will be written as $v(d_1 \cup d_2 \cup d_3)$. The specific value of the payoff function can be determined using appropriate process integration (PI) methods, which need to be applied to every possible coalition that can be formed from a given set of companies or plants.
- Given the payoff for every possible sub-coalition, including the *grand coalition* that involves all partners, the problem is to determine a rational and equitable allocation of the benefits among the partners. In this chapter, the cooperative game model introduced by Maali (2009) is adapted to determine the allocation.

9.3 Cooperative Game Model

A mathematical programming-based approach to the benefits sharing problem was recently proposed as an alternative to well-established concepts such as the Shapley value (Shapley, 1953). Maali's cooperative game model (Maali, 2009) is developed based on max-min aggregation method where the optimum solution is obtained by maximising the least satisfied constraints. Figure 9.1 summarises the detailed steps of the cooperative game model. As shown, the companies/plants d that are interested in sharing utilities and exchanging by-products with others are first identified. Mass and heat balance for all plants are modeled with appropriate techniques. Next, the characteristic function $v(S)$ (e.g., potential savings cost, etc.) is defined. In practice, the characteristic function needs to be evaluated for every possible coalition comprised of all, or a subset, of the plants in the system. The evaluation may be done using PI methodology (i.e., pinch analysis, mathematical programming or hybrid techniques) to account for case-specific economic and physical aspects. In effect, such methods act as the inner model to evaluate $v(S)$ (as shown in the fourth step of Figure 9.1), which is embedded within the outer cooperative game model. All $v(S)$ values are compiled and then followed by application of the cooperative game model to derive appropriate shares for partners in an industrial symbiosis (IS) coalition.

The cooperative game model is solved by imposes the optimisation objective as maximising the lowest degree of satisfaction, β, based on max-min aggregation, which is given as:

$$\text{Max } \beta \qquad (9.1)$$

Equation (9.2) is then formulated as allocation constraints based on the marginal contribution C_d of each company to any coalition it joins. This marginal contribution C_d is known as average difference in payoff contributed by each player to every possible coalition or the weightage of payoffs of companies/plants x_d.

$$\frac{1}{C_d} x_d \geq \beta \qquad \forall d \qquad (9.2)$$

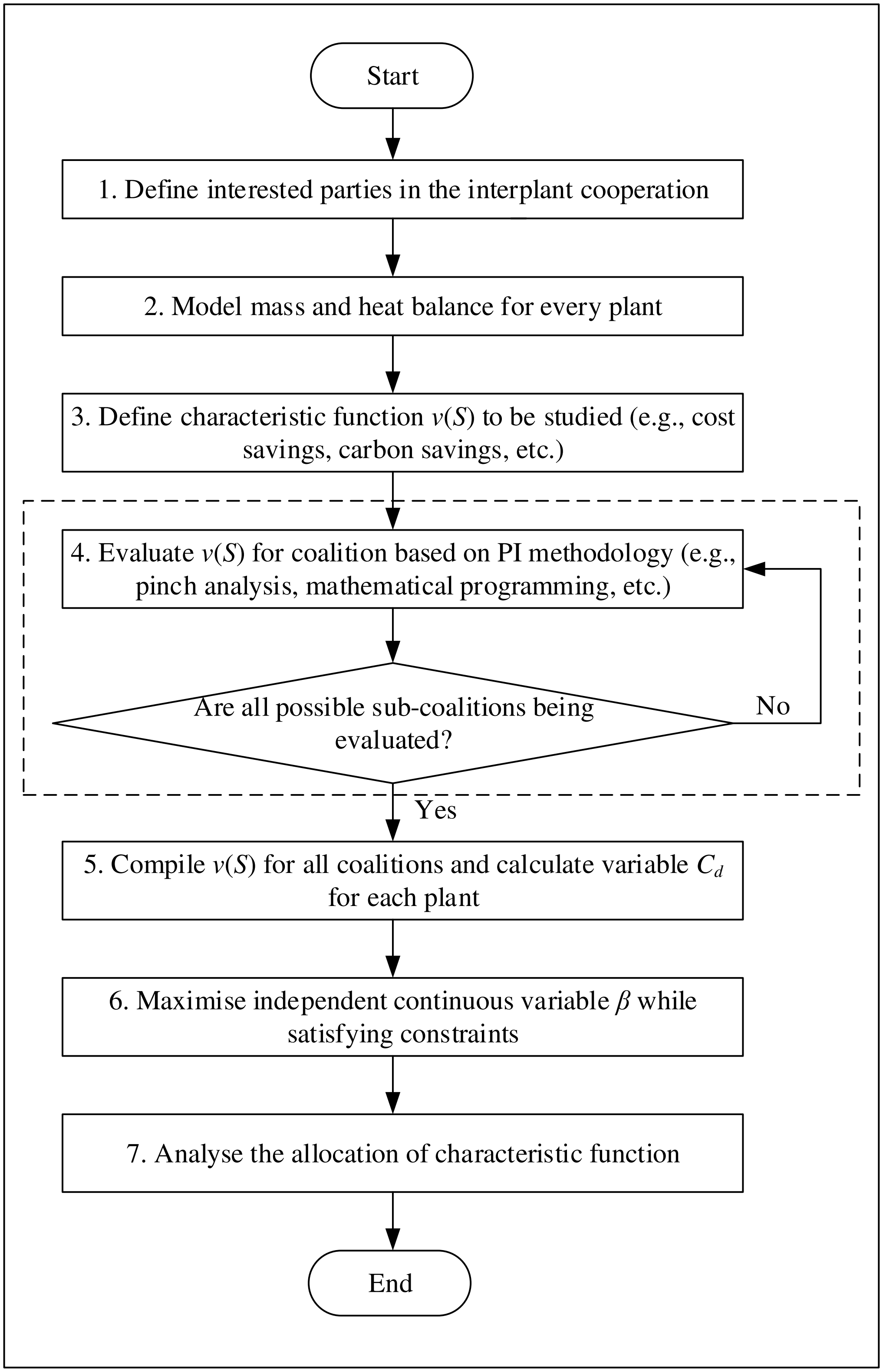

Figure 9.1: Flowchart of Maali's cooperative game model

This weightage can be determined based on the incremental contribution of companies/plants, x_d in a coalition as shown in Equation (9.3),

$$C_d = \sum_S [v(S) - v(S - \{d\})] / v(\aleph) \qquad \forall d \qquad (9.3)$$

where $v(S)$ represents the payoffs for a coalition S while $v(S\text{-}\{d\})$ is the payoffs of a coalition without companies/plants d. Meanwhile, $v(\aleph)$ is the payoffs for *grand coalition*. In order to ensure individual rationality in the game (i.e., the benefits that accrue from cooperation cannot be less than the benefits a company stands to gain on its own), Equation (9.4) is formulated.

$$x_d \geq v(\{d\}) \qquad \forall d \qquad (9.4)$$

Finally, Equation (9.5) is formulated to ensure group rationality (i.e., all payoffs are fully accounted for when allocated to the different participants).

$$\sum_d x_d = v(\aleph) \qquad \forall d \qquad (9.5)$$

This cooperative game model is demonstrated in the succeeding sections with two illustrative examples. The first example is a relatively simple heat integration literature case study, and is intended as a pedagogic case that illustrates the outer cooperative game model. Then, an industrial case study is given to demonstrate the overall framework, including the PI models nested within the outer cooperative game model. This case study demonstrates the allocation of cost savings.

9.4 Literature Case Study

A case study from the literature example (Hiete et al., 2012) is resolved to demonstrate the proposed approach. In this case study, four companies (A = pulp production, B = bio-oil production, C = fiberboard and D = torrefaction) are located in an industrial cluster. All companies are interested in forming an EIP to promote heat integration within the industrial cluster. Table 9.1 tabulates the potential savings from different coalitions as reported by Hiete et al. (2012). Note that the values are obtained from pinch analysis, using established PI methods to determine the potential for savings for all coalitions of subsets of the four industrial plants. The reader may refer to Hiete et al. (2012) for details.

Table 9.1: Comparison of savings arising from different coalitions (Hiete et al., 2012)

Coalition $v(S)$	Potential savings compared to individual process integration (10^3 USD)
{A}	–
{B}	–
{C}	–
{D}	–
{A,B}	13
{A,C}	18
{A.D}	129
{B,C}	121
{B,D}	0
{C,D}	0
{A,B,C}	130
{A,B,D}	142
{A,C,D}	146
{B,C,D}	121
{A,B,C,D}	259

The distribution of potential savings for all companies is performed via the proposed approach. Coalition values between four companies in Table 9.1 are used to calculate the values of the marginal contributions, C_d via Equation (9.3). This gives Equations (9.4) – (9.7).

$$C_{\mathrm{A}} = \begin{bmatrix} v(\mathrm{A}) + v(\mathrm{A,B}) - v(\mathrm{B}) + v(\mathrm{A,C}) - v(\mathrm{C}) + v(\mathrm{A,D}) - v(\mathrm{D}) \\ + v(\mathrm{A,B,C}) - v(\mathrm{B,C}) + v(\mathrm{A,B,D}) - v(\mathrm{B,D}) \\ + v(\mathrm{A,C,D}) - v(\mathrm{C,D}) + v(\mathrm{A,B,C,D}) - v(\mathrm{B,C,D}) \end{bmatrix} / v(\mathrm{A,B,C,D}) \tag{9.4}$$

$$C_{\mathrm{B}} = \begin{bmatrix} v(\mathrm{B}) + v(\mathrm{A,B}) - v(\mathrm{A}) + v(\mathrm{B,C}) - v(\mathrm{C}) + v(\mathrm{B,D}) - v(\mathrm{D}) \\ + v(\mathrm{A,B,C}) - v(\mathrm{A,C}) + v(\mathrm{A,B,D}) - v(\mathrm{A,D}) \\ + v(\mathrm{B,C,D}) - v(\mathrm{C,D}) + v(\mathrm{A,B,C,D}) - v(\mathrm{A,C,D}) \end{bmatrix} / v(\mathrm{A,B,C,D}) \tag{9.5}$$

$$C_{\mathrm{C}} = \begin{bmatrix} v(\mathrm{C}) + v(\mathrm{A,C}) - v(\mathrm{A}) + v(\mathrm{B,C}) - v(\mathrm{B}) + v(\mathrm{C,D}) - v(\mathrm{D}) \\ + v(\mathrm{A,B,C}) - v(\mathrm{A,B}) + v(\mathrm{A,C,D}) - v(\mathrm{A,D}) \\ + v(\mathrm{B,C,D}) - v(\mathrm{B,D}) + v(\mathrm{A,B,C,D}) - v(\mathrm{A,B,D}) \end{bmatrix} / v(\mathrm{A,B,C,D}) \tag{9.6}$$

$$C_{\mathrm{D}} = \begin{bmatrix} v(\mathrm{D}) + v(\mathrm{A,D}) - v(\mathrm{A}) + v(\mathrm{B,D}) - v(\mathrm{B}) + v(\mathrm{C,D}) - v(\mathrm{C}) \\ + v(\mathrm{A,B,D}) - v(\mathrm{A,B}) + v(\mathrm{A,C,D}) - v(\mathrm{A,C}) \\ + v(\mathrm{B,C,D}) - v(\mathrm{B,C}) + v(\mathrm{A,B,C,D}) - v(\mathrm{A,B,C}) \end{bmatrix} / v(\mathrm{A,B,C,D}) \tag{9.7}$$

After the coalition values shown in Table 9.1 are substituted in Equations (9.4) – (9.7), Equations (9.12) – (9.16) is formed. A calculation example is given for company A as shown in following example Equations (9.8) – (9.11),

$$C_{\mathrm{A}} = \begin{bmatrix} 0 + 13 - 0 + 18 - 0 + 129 - 0 + 130 - 121 + 142 - 0 \\ +146 - 0 + 259 - 121 \end{bmatrix} / 259 \tag{9.8}$$

$$C_{\mathrm{A}} = [595] / 259 \tag{9.9}$$

$$C_A = 2.297 \tag{9.10}$$

$$\frac{1}{C_A} = 0.4353 \tag{9.11}$$

Thus, in this literature case study, the LP cooperative game model is:

$$\text{Max } \beta \tag{9.12}$$

Subject to

$$0.4353x_A \geq \beta \tag{9.13}$$

Same calculation is applied to company B, C, D and Equations (9.14) – (9.16) are formed.

$$0.5254x_B \geq \beta \tag{9.14}$$

$$0.5068x_C \geq \beta \tag{9.15}$$

$$0.5029x_D \geq \beta \tag{9.16}$$

In order to ensure individual and group rationality in the game, Equations (9.17) – (9.18) are given.

$$x_A, x_B, x_C, x_D, \beta \geq 0 \tag{9.17}$$

$$x_A + x_B + x_C + x_D \geq 259{,}000 \tag{9.18}$$

This cooperative game model is then solved via LINGO v13.0. The result for the literature case study is tabulated in Table 9.2. Based on the optimised result, the savings of Companies A, B, C and D are approximately of USD 72,900, USD 60,400, USD 62,610 and USD 63,100 respectively.

Table 9.2: Detailed saving allocation of each company in illustrative example

Company	Potential savings (10^3 USD)
A	72.90
B	60.40
C	62.60
D	63.10
Total	259.00

The result obtained from the proposed Maali's method is then compared with the results obtained from different cooperative game techniques – Shapley value and alternate cost avoided (ACA). Details pertaining to Shapley value and ACA methods from this literature case study can be found in Hiete et al. (2012). Figure 9.2 shows the comparison of the proposed method, Shapley value and ACA. As shown, Maali's method gives a somewhat more equitable distribution as compared to other cooperative game techniques; Companies B and C which with all cooperative game methods receive the smallest shares in the coalition, receive slightly greater benefits using this approach, as compared to the results of Shapley value and ACA methods.

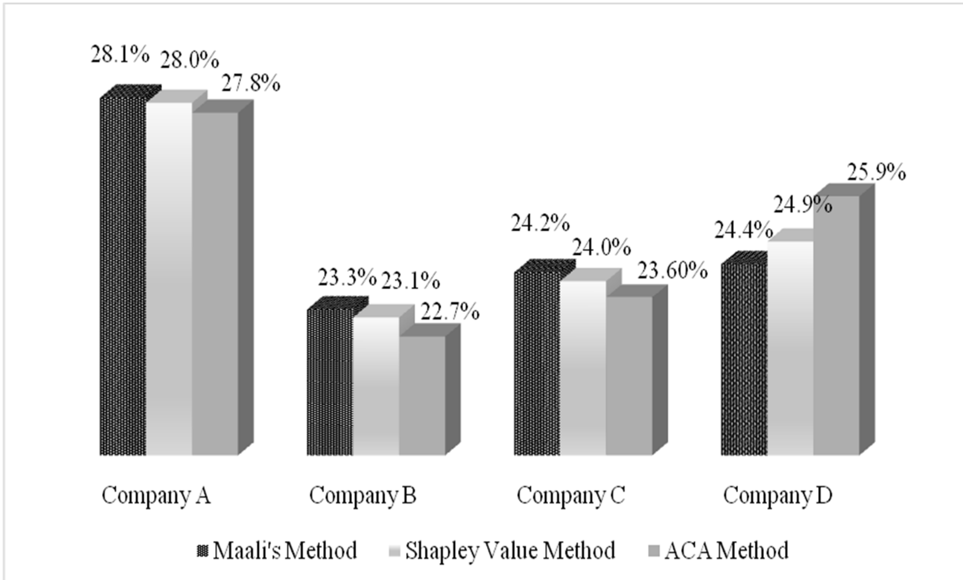

Figure 9.2: Comparison of Maali's and Shapley value in literature case study

9.5 Sago Industrial Case Study

As mentioned in previous chapters, sago biomass such as sago barks, sago fibres, and sago wastewater are generated during sago starch extraction process (SSEP). Such biomasses are currently discharged to the environment and cause severe environment impacts. As reported in Chapters 7 and 8, sago barks and fibres could be converted into combined heat and power and bioethanol via a biomass-based combined heat and power (CHP) system and sago-based bioethanol plant (SBP). Therefore, in order to reduce such environmental pollutants and to increase economic performance of sago industry, conversion of sago biomass into such value-added products is of paramount importance. In others word, sago biomass-based CHP plant and SBP are vital to be implemented. In addition, in line with the global efforts in sustainable development, as mentioned in Chapter 2, the concept of integrated biorefinery is important to be adopted for more sustainable productions, competitive economic operation and environmental performance. Hence, SSEP, sago-based CHP system, and SBP as well as wastewater treatment plant (WWTP) are encouraged to be integrated to form an integrated sago-based biorefinery (SBB) to improve sustainability of sago industry. In order to encourage the plants owners (i.e., SSEP, CHP system, WWTP, and SBP) to participate in integrated SBB, determination of deserve benefits of each plants in integrated SBB is paramount of importance since every plant is a “self-interested maximiser of individual profit”, as noted by Jackson and Clift (1998). In this chapter, economic performance (i.e., cost savings) of each participating plant in the integrated SBB is analysed via the proposed approach.

In this chapter, an integrated SBB is envisaged as shown in Figure 9.3. As shown, sago biomasses (sago barks and fibres) are used as feedstock in CHP plant and SBP to generate steam and electricity as well as bioethanol. Meanwhile, sago wastewater is transferred to WWTP for treatment and to produce treated water that can be reused/recycled to SSEP and SBP. In CHP plant, part of the generated steam can be supplied to SBP for bioethanol production and SSEP for drying purpose. The remaining steam is converted into electricity in the CHP plant for use by the SSEP, SBP, and WWTP. The excess electricity (if any) can be exported to the grid. In the SBP, high pressure steam (HPS) and low pressure steam (LPS) are required to produce bioethanol. Besides the bioethanol, wastewater and lignin are also generated as by-products in SBP. The wastewater can be transferred to WWTP for treatment to generate more biogas, while the lignin can be transferred to CHP plant directly as fuel to generate more electricity. The WWTP is configured to convert wastewater into biogas while treating wastewater to comply with regulatory discharge limits. This biogas is used by the CHP plant for more electricity generation.

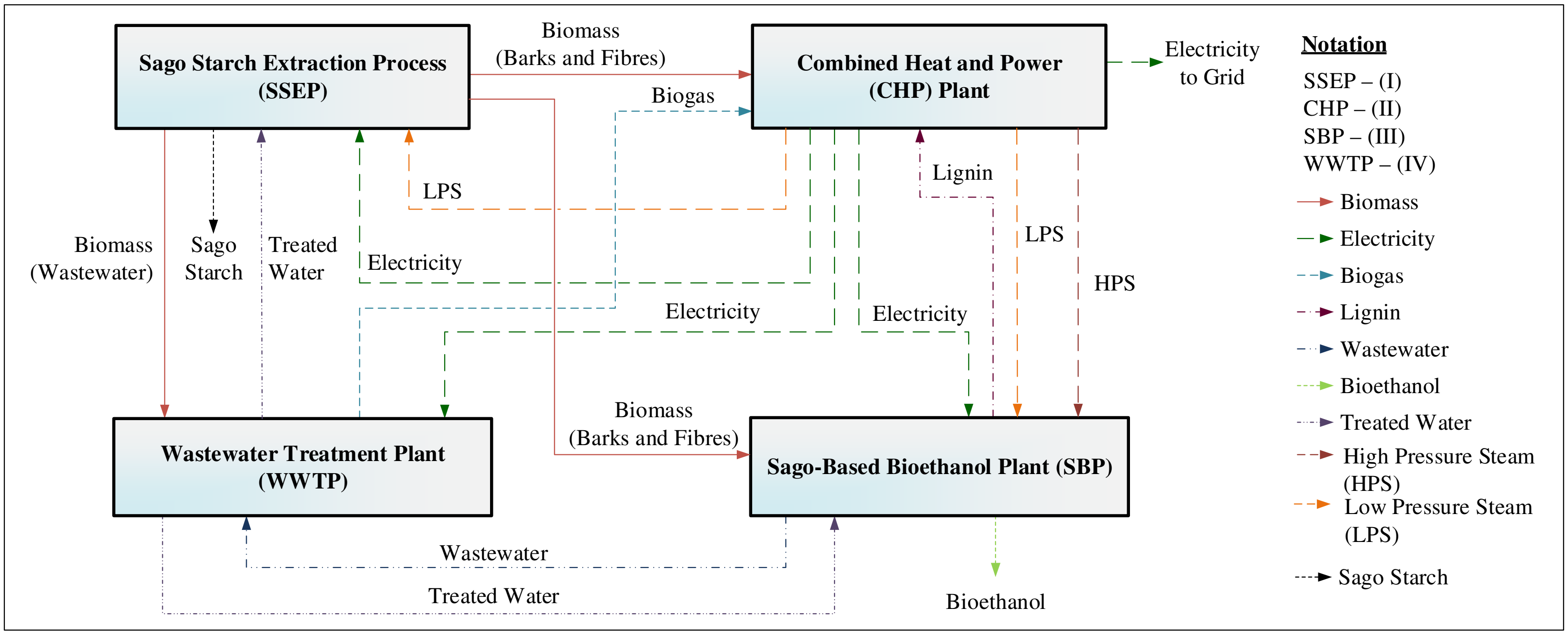

Figure 9.3: Block diagram of integrated SBB in industrial case study

In this chapter, 24 t/d of SSEP is used as baseline. Note that the process of SBP using biochemical conversion technology, and the biological WWTP, as well as the CHP plant as presented in Chapter 7 and Chapter 8 are adapted in this case. The mass and heat balances for the integrated SBB are determined via a spreadsheet-based yield prediction model and Aspen Plus simulation as presented in Chapter 7 and Chapter 8. Based on the information shown in Tables 9.3 – 9.5 which extracted from Chapters 5, 7, and 8, total potential cost savings for each coalition is determined as shown in Table 9.6. As shown in Table 9.6, the integrated SBB consists of Plant I (SSEP), Plant II (CHP), Plant III (SBP), and Plant IV (WWTP). As shown, the grand coalition {I, II, III, IV} gives the highest total potential cost savings amongst all the coalitions. This coalition is illustrated in Figure 9.4.

Table 9.3: Calorific value and available amount of sago barks, fibres, lignin, and biogas

	Sago Barks	Sago Fibres	Lignin	Biogas
Calorific value (kJ/g)	19.27	14.25	11.14	12.54
Available amount of biomass (wet basis) (t/d)	41.60	33.80	7.93	4.56 (generated from wastewater of SBP) 3.68 (generated from wastewater of SSEP)
Moisture content of wet biomass (%)	51.00	62.00	N/A	N/A
Available amount of biomass (dry basis) (t/d)	20.40	12.80	N/A	N/A

Table 9.4: Units costs of raw material and utilities

	Unit Cost	
Sago logs	2.8	USD/log
Raw water	0.33	USD/m^3
Electricity	0.11	USD/kWh
Steam	0.026	USD/kg
Sago barks	10	USD/t
Sago fibres	10	USD/t
Wastewater treatment cost	0.02	USD/PE

Note: 0.13kgCOD = 1 population equivalent (PE)

Table 9.5: Utilities consumption

	Utility Consumption	
Raw water		
SSEP	486.0	m^3/d
SBP	97.5	m^3/d
Electricity		
SSEP	3890.0	kWh
SBP	3193.4	kWh
WWTP	2692.08	kWh
Steam		
SSEP	25.64	t/d
SBP	24.19	t/d
	Wastewater Generation	
SSEP	552.00	t/d
SBP	77.05	t/d

Table 9.6: Potential cost savings for each coalition in integrated SBB for industrial case study

Coalition $v(S)$	Potential Cost Savings (USD/d)
{I}	-
{II}	-
{III}	-
{IV}	-
{I, II}	1,138.22
{I, III}	377.00
{I, IV}	1,131.05
{II, III}	980.22
{II, IV}	296.13
{III, IV}	790.82
{I, II, III}	2,828.76
{I, II, IV}	2,898.72
{I, III, IV}	2,298.87
{II, III, IV}	2,067.17
{I, II, III, IV}	5,046.76

As with the previous literature case study, Equations (9.2) is used to generate Equations (9.19) – (9.22).

$$C_{\text{I}} = \begin{bmatrix} v(\text{I}) + v(\text{I,II}) - v(\text{II}) + v(\text{I,III}) - v(\text{III}) + v(\text{I,IV}) - v(\text{IV}) \\ + v(\text{I,II,III}) - v(\text{II,III}) + v(\text{I,II,IV}) - v(\text{II,IV}) \\ + v(\text{I,III,IV}) - v(\text{III,IV}) + v(\text{I,II,III,IV}) - v(\text{II,III,IV}) \end{bmatrix} / v(\text{I,II,III,IV}) \tag{9.19}$$

$$C_{\text{II}} = \begin{bmatrix} v(\text{II}) + v(\text{I,II}) - v(\text{I}) + v(\text{II,III}) - v(\text{III}) + v(\text{II,IV}) - v(\text{IV}) \\ + v(\text{I,II,III}) - v(\text{I,III}) + v(\text{I,II,IV}) - v(\text{I,IV}) \\ + v(\text{II,III,IV}) - v(\text{III,IV}) + v(\text{I,II,III,IV}) - v(\text{I,III,IV}) \end{bmatrix} / v(\text{I,II,III,IV}) \tag{9.20}$$

$$C_{\text{III}} = \begin{bmatrix} v(\text{III}) + v(\text{I,III}) - v(\text{I}) + v(\text{II,III}) - v(\text{II}) + v(\text{III,IV}) - v(\text{IV}) \\ + v(\text{I,II,III}) - v(\text{I,II}) + v(\text{I,III,IV}) - v(\text{I,IV}) \\ + v(\text{II,III,IV}) - v(\text{II,IV}) + v(\text{I,II,III,IV}) - v(\text{I,II,IV}) \end{bmatrix} / v(\text{I,II,III,IV}) \tag{9.21}$$

$$C_{IV} = \begin{bmatrix} v(IV)+v(I,IV)-v(I)+v(II,IV)-v(II)+v(III,IV)-v(III) \\ +v(I,II,IV)-v(I,II)+v(I,III,IV)-v(I,III) \\ +v(II,III,IV)-v(II,III)+v(I,II,III,IV)-v(I,II,III) \end{bmatrix} / v(I,II,III,IV) \quad (9.22)$$

After the coalition values shown in Table 9.6 are substituted in Equations (9.19) – (9.22), Equations (9.23) – (9.29) are formed. The fair allocation of potential cost savings of each plant in integrated SBB is then determined by maximising β and the results are summarised in Table 9.7.

$$\text{Max } \beta \quad (9.23)$$

Subject to

$$0.4356x_{I} \geq \beta \quad (9.24)$$

$$0.4735x_{II} \geq \beta \quad (9.25)$$

$$0.5654x_{III} \geq \beta \quad (9.26)$$

$$0.5482x_{IV} \geq \beta \quad (9.27)$$

$$x_{I}, x_{II}, x_{III}, x_{IV}, \beta \geq 0 \quad (9.28)$$

$$x_{I} + x_{II} + x_{III} + x_{IV} = 5046.76 \quad (9.29)$$

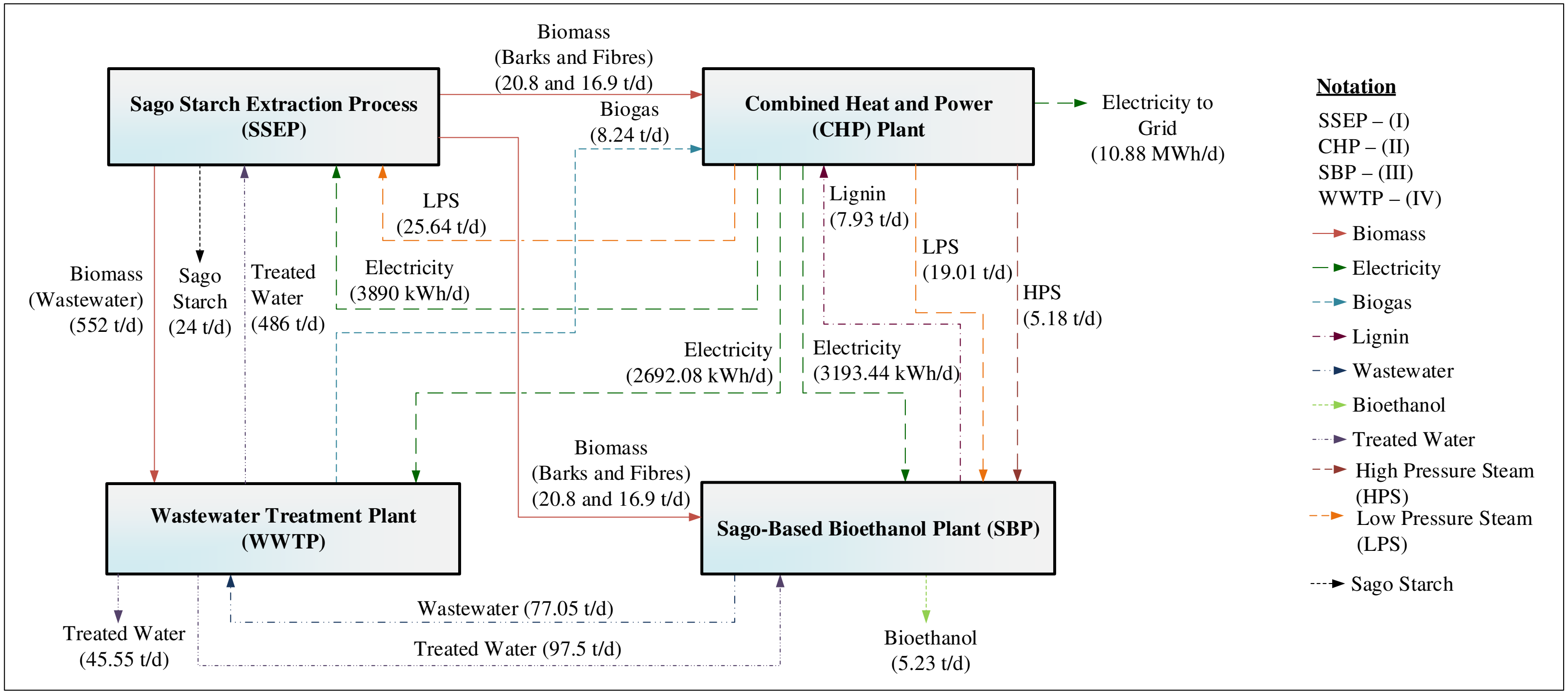

Figure 9.4: Coalition diagram with the highest potential cost savings for integrated SBB

It can be seen that cost savings are greater when plants cooperate to form integrated SBB, as compared to non-integrated stand-alone operation. A total cost of USD 5,046.76 can be saved per day. The cooperative game model proposed here provides a sound basis for facilitating negotiations among companies or plants that comprise the integrated SBB.

Table 9.7: Allocated potential cost savings for each plant in integrated SBB

Plants	Potential Cost Savings (USD/d)
I	1,448.13
II	1,332.28
III	1,115.69
IV	1,150.67
Total	5,046.76

9.6 Comparison between Maali's Cooperative Game Model and Shapley Value

The classical cooperative game method known as the Shapley value (Shapley,1953) is used as basis for validating the results from the approach proposed here. The formula for the Shapley value is:

$$x_d = \sum_{S \subseteq N \setminus \{d\}} \frac{|S|!\,(n-|S|-1)!}{n!}\left[v(S \cup \{d\}) - v(S)\right] \qquad \forall\ d \tag{9.30}$$

The Shapley value method (shown in Equation 9.20) is compared with the results obtained from Maali's cooperative game model. Note that the bracketed quantity is similar to the marginal contribution in Equation 9.3, but it is multiplied by a probabilistic weight factor based on permutations of coalition formation. Figure 9.5 shows the comparison of the proposed method with the Shapley value method for sago industrial case study. The two methods yield similar results, thus demonstrating that Maali's method proves to be a useful alternative to express cooperative games in the form of an optimisation problem. Thus, this technique may allow PI models to be algorithmically embedded within a larger game-theoretic model. Furthermore, this approach is more flexible than the Shapley value, as case-specific weight factors can be readily inserted in the model to adjust allocation of benefits among partners. In addition, the presented approach can be used as a pre-negotiation tool, to provide a rational starting point for companies to analyse and engage in future cooperative partnerships.

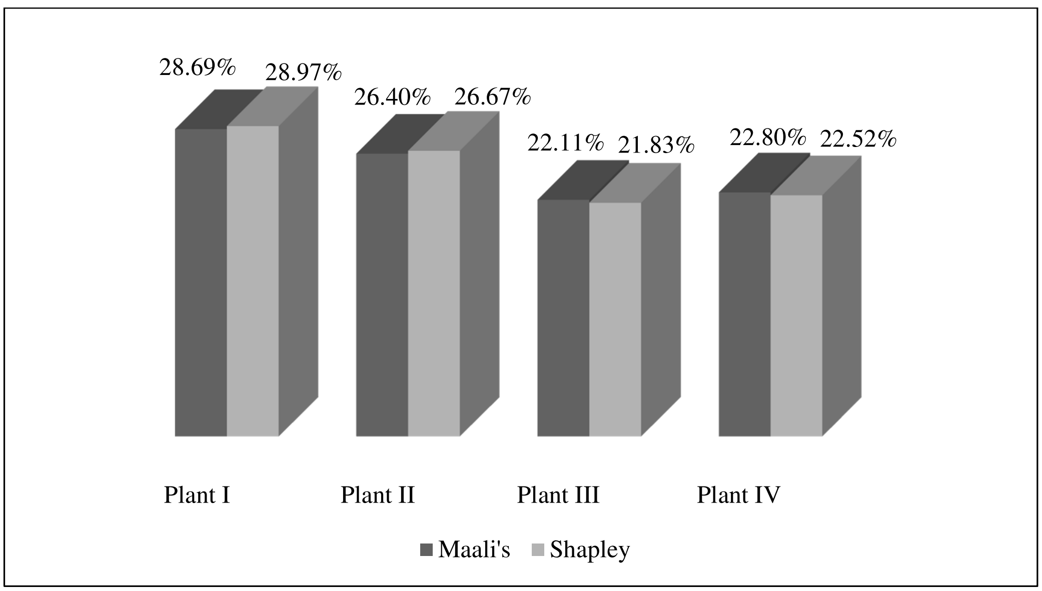

Figure 9.5: Comparison of Maali's method and Shapley value for integrated SBB in sago industrial case study

9.7 Summary

In this chapter, an approach to the optimal allocation of costs and benefits in cooperative interplant process integration in eco-industrial parks has been demonstrated. This approach is based on the cooperative game approach developed by Maali (2009), which uses an LP formulation to determine the appropriate shares, given the potential benefit determined for every possible sub-coalition. A nested framework is developed where a PI inner model is embedded within the outer cooperative game model. This methodology has been applied to a literature case study and a sago industrial case study to demonstrate how equitable sharing of benefits of PI can be achieved in a planned EIP.

CHAPTER 10

CONCLUSIONS AND FUTURE WORKS

10.1 Conclusions

In this thesis, several novel approaches have been developed to improve sustainability of sago industry. Significant contributions have been offered in the area of value chain synthesis, waste recovery, Resources Conservation Networks (RCNs) with industrial processes synthesis, techno-economic performance evaluation, and benefits allocation in Eco-industrial Park (EIP). The key contributions are summarised as the followings:

i. Fuzzy Multi-Footprint Optimisation (FMFO) approach, which considers multiple footprints (i.e., carbon, water, workplace footprints) and economic performance, is developed to synthesise an optimum value chain. Fuzzy optimisation is adapted in this approach to address multiple objective functions that are often contradictory. This enable the proposed approach to use as an analysis tool that aids decision makers in pathway selection with multiple objective functions. Via this FMFO approach, a sustainable sago value chain with maximum economic performance and minimum environmental impacts and occupational casualty is synthesised.

ii. Material Flow Cost Accounting (MFCA)-based prioritisation approach, which incorporated the concept of MFCA, is developed for prioritisation of waste recovery. This approach introduced hidden cost (HC) and carry-forward cost (CFC) to prioritise the waste streams to be recovered. This approach determined the cost associated with waste streams. Based on this associated cost, prioritisation of waste recovery in sago starch extraction process (SSEP) is performed. This is a novel prioritisation approach for waste recovery in the case where the quality and quantity of waste streams to be recovered are same.

iii. Material Flow Cost Accounting (MFCA)-based prioritisation approach is further extended to simultaneous synthesis of Resource Conservation Networks (RCNs) and industrial processes. The extended MFCA (eMFCA)-based prioritisation approach considered industrial costs, quality and quantity of waste streams in resources recovery. This approach synthesise an optimum RCN and industrial processes simultaneously with maximum economic performance. In this thesis, an optimum total water network and SSEP with minimum waste generation cost is synthesised via the proposed approach.

iv. Techno-economic and environmental evaluation on the utilisation of sago biomass is performed in this thesis to examine the feasibility of sago-based combined heat and power (CHP) plant in Malaysia context. Three different conventional configurations of CHP system are adopted and being analysed. Different scenarios (i.e., with on-site or off-site pre-treatment, hiring new labour or making use of current labour) are subsequently proposed to analyse the impact of labour cost and feedstock cost on economic performance of a CHP system. Sensitivity analysis is also conducted based on existence of pre-treatment, variations in feedstock cost, boiler efficiency, and biomass type.

v. Techno-economic and environmental performance evaluation of integrated sago-based bioethanol plant (SBP) and energy systems is performed in Malaysia context to examine its feasibility. A conceptual integrated sago-based biorefinery (SBB), which composed of sago starch extraction process (SSEP), CHP plant, SBP and wastewater treatment plant (WWTP), is envisioned and analysed based on the bioethanol plant study conducted by the National Renewable Energy Laboratory (NREL). Various feedstocks (i.e., sago fibres, barks, and combined biomass (fibres and barks)) and scenarios (i.e., with on-site and off-site enzyme production) are considered in the performance evaluations. The impact of labour cost on economic performance of integrated SBB is also evaluated.

vi. An optimisation-based cooperative game approach is proposed for rational and defensible allocation of benefits of each party participated in an EIP. In this thesis, the deserve benefits (i.e., cost savings) of each plant participated in integrated SBB is determined. As results, cost savings are greater when plants cooperate to form integrated SBB, as compared to non-integrated stand-alone operation. This approach provides a sound basis for facilitating negotiations among companies or plants that comprise the EIP.

10.2 Future Works

Several future works of this thesis are summarised as the followings:

i. Robust optimisation approach with uncertainties for synthesis of sustainable value chain

   As presented in Chapter 4, the proposed model is data-intensive and initially customised for the sago industry; however, it is still generic enough to be applied in different crop value chains with some modifications. The problem of data availability might be encountered in the case of underutilised or new commercial crops. Hence, dealing with the uncertainties of data can be considered in the future for the development of sustainable value chains via robust optimisation.

ii. Extended Fuzzy Multi-Footprint Optimisation (eFMFO) approach for sustainable value chain synthesis

   In Chapter 4, only production of sago starch is being considered in the sago value chain. Hence, the approach proposed in Chapter 4 can be further extended by considering sago biomass as potential raw materials for generating by-products that contribute environmental and economic benefits to the sago value chain.

iii. Life Cycle Analysis (LCA)-based techno-economic evaluation for feasibility of an integrated biorefinery

In Chapters 7 and 8, it is noted that only CO_2 emission reduction is used to assess the environmental performance. However, conversion of sago biomass into bioethanol and combined heat and power also reduces other environmental issues, such as river pollution. Therefore, the environmental assessment could be further extended by considering other assessments such as water footprint, sustainability index, etc. Besides, it is noted that the environmental performance evaluation conducted in Chapter 8 is limited to the emissions from the CHP system and bioethanol plant of integrated SBB. This could be further extended by having a more complete environmental analysis of the system using life cycle analysis (LCA).

iv. Disjunctive optimisation-based cooperative game approach for benefits allocation in Eco-Industrial Park

The approach proposed in Chapter 9 can be further extended by integrating the game theoretic model with a unified disjunctive programming network synthesis model, which will allow the optimal configuration and sharing of benefits to be determined in a single step. Furthermore, the cooperative game framework should be extended to address practical issues, such as seasonal operations of plants and consideration of multiple objectives.

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APPENDICES

(For full version of appendices, it can be referred to the softcopy in the attached CD-R.)

APPENDIX A

SUPPORTING DOCUMENTS OF CHAPTER 4

List of Tables

Table A1: Related information of sago starch value chain in Sarawak, Malaysia

Plantations[1,2,3], g	Available palms, Z_g^{Palm} (palm/y)	Extractable starch, $L_{g,starch}$ (t/log)	Sago Mills, f	Capacity[1], $Z_{f,p}$ (t/y)
Mukah	571,780	0.022	Mukah A	13,200
Dalat	4,209,840	0.024	Mukah B	8,250
Saratok	343,260	0.018	Dalat A	7,260
Betong	755,200	0.020	Dalat B	8,250
			Dalat C	8,250
			Pusa	3,960
Customers[4], u	**Demand, $D_u^{Starch\_UL}$ (t/y)**	**Demand, $D_u^{Starch\_LL}$ (t/y)**	**Ports, j**	**Capacity, Z_j (t/y)**
Japan	13,000	12,500	[5]Kuching	7,000,000
P. Malaysia	30,700	30,000	[6]Sibu	450,000
Singapore	3,000	2,500	[7]Miri	53,900
Thailand	1,300	1,000		

[1]Data is estimated based on the input from sago mills owners; or published data from [2]Flach (1997); [3]Gerbens-Leenes and Hoekstra (2011); [4]DOA (n.d.); [5]Kuching Port Authority (n.d.); [6]Rajang Port Authority (n.d.); [7]Miri Port Authority (n.d.)

Table A2: Estimated distances between plantation and sago mills (km) (Google Maps, 2014)

Plantation – Sago Mills	Distances, $d_{g,y,f}$ (km)															Distances, $d_{g,f}$ (km)
	KCH	SMH	SRN	SMJ	SA	BTG	SRT	SRK	MRD	SB	DLT	MUK	TT	BTL	MR	Total
Mukah - Mukah A												76				76
Mukah - Mukah B												61				61
Mukah - Dalat A											63	14				77
Mukah - Dalat B											70	14				84
Mukah - Dalat C											58	14				72
Mukah - Pusa						19	27	62	28	55	23	14				228
Dalat - Mukah A											13	76				89
Dalat - Mukah B											13	61				74
Dalat - Dalat A											63					63
Dalat - Dalat B											70					70
Dalat - Dalat C											58					58
Dalat - Pusa						19	27	62	28	55	11					202
Saratok - Mukah A							7	62	28	55	23	76				251
Saratok - Mukah B							7	62	28	55	23	61				236
Saratok - Dalat A							12	62	28	55	14					171
Saratok - Dalat B							12	62	28	55	7					164
Saratok - Dalat C							12	62	28	55	19					176
Saratok - Pusa						19	27									46
Betong - Mukah A						33.4	27	62	28	55	23	76				304.4
Betong - Mukah B						33.4	27	62	28	55	23	61				289.4
Betong - Dalat A						33.4	27	62	28	55	14					219.4
Betong - Dalat B						33.4	27	62	28	55	7					212.4
Betong - Dalat C						33.4	27	62	28	55	19					224.4
Betong - Pusa						56.3										56.3

Table A3: Estimated distances between sago mills to ports (km) (Google Maps, 2014)

Sago Mills - Ports	Distances, $d_{f,y,j}$ (km)															Distances, $d_{f,j}$ (km)
	KCH	SMH	SRN	SMJ	SA	BTG	SRT	SRK	MRD	SB	DLT	MUK	TT	BTL	MR	Total
Mukah A - Kuching	8	12	84	18.5	110	10	27	62	28	55	23	76				513.5
Mukah B - Kuching	8	12	84	18.5	110	10	27	62	28	55	23	61				498.5
Dalat A - Kuching	8	12	84	18.5	110	10	27	62	28	55	14					428.5
Dalat B - Kuching	8	12	84	18.5	110	10	27	62	28	55	7					421.5
Dalat C - Kuching	8	12	84	18.5	110	10	27	62	28	55	19					433.5
Pusa - Kuching	8	12	84	18.5	110	56.3										288.8
Mukah A - Sibu										39	23	76				138
Mukah B - Sibu										39	23	61				123
Dalat A - Sibu										39	14					53
Dalat B - Sibu										39	7					46
Dalat C - Sibu										39	19					58
Pusa - Sibu						19	27	62	28	55						191
Mukah A - Miri												137	34	92	151	414
Mukah B - Miri												122	34	92	151	399
Dalat A - Miri											9	72	34	92	151	358
Dalat B - Miri											16	72	34	92	151	365
Dalat C - Miri											4	72	34	92	151	353
Pusa - Miri						19	27	62	28	55	24	72	34	92	151	564

Table A4: Estimated distances between ports and customers (km) (Port.com)

Distances, $d_{j,u}$ (km)	Japan (Yokohama)	P. Malaysia (Klang)	Singapore (Singapore)	Thailand (Bangkok Modern)
Kuching	6154.5	1362.1	1000.7	2262.8
Sibu	5809.8	1519.6	1158.3	2353.6
Miri	5502.2	1829.1	1467.7	2396.2

Table A5: Unit cost of harvesting, processing, handling and transportation and unit selling price of sago logs and sago starch

	Unit Cost of Sea Transportation, $UCost_{j,u}^{Port\_Cust}$ (MYR/trip)				Unit Selling Price of Sago Starch, $SP_{j,u}^{Starch}$ (MYR/kg)				Handling Cost, $UCost_{j}^{Handling}$ (MYR/container)
	Japan	P. Malaysia	Singapore	Thailand	Japan	P. Malaysia	Singapore	Thailand	
Kuching	3,960	1,650	1,485	2,640	1.9	1.6	1.7	1.8	1,500
Sibu	3,729	1,980	1,584	2,805	1.9	1.6	1.7	1.8	1,300
Miri	3,531	2,310	1,650	2,970	1.9	1.6	1.7	1.8	1,200

	Unit Cost and Selling Price of Log, $UCost_{g,f}^{Log}$, $SP_{g,f}^{Log}$ (MYR/log)	Harvesting Cost, $UCost_{g}^{Harv}$ (MYR/palm)
Mukah	10	3.8
Dalat	12	4.2
Saratok	8	3.0
Betong	9	3.6

Road Transportation cost, UC^{Road} (MYR/km)	4.5

	Unit Cost and Selling Price of Sago Starch, $UCost_{f,j}^{Starch}$, $SP_{f,j}^{Starch}$ (MYR/kg)			Processing Cost, $UCost_{f,p}^{Process}$ (MYR/t)
	Kuching	Sibu	Miri	
Mukah A	1.6	1.5	1.55	108
Mukah B	1.6	1.5	1.55	115
Dalat A	1.6	1.5	1.55	117
Dalat B	1.6	1.5	1.55	112
Dalat C	1.6	1.5	1.55	122
Pusa	1.6	1.5	1.55	95

**1 MYR = 0.30 USD*

Table A6: Death (D), non-permanent disability (NPD) and permanent disability (PD) risk of harvesting, processing, handling, road and sea transportation

Road Transportation Risk, $r_y^{Road} \times 10^{-14}$

	D/km	NPD/km	PD/km
Kuching	156	239	234
Samarahan	2.78	13.9	2.78
Serian	27.8	19.5	100
Simunjan	8.34	2.78	75.1
Sri Aman	103	97.3	8.34
Betong	27.8	8.34	22.2
Saratok	16.7	2.78	58.4
Sarikei	47.3	91.8	111
Maradong	0.00	0.00	0.00
Sibu	114	0.00	2.78
Dalat	2.78	13.9	2.78
Mukah	27.8	8.34	22.2
Tatau	33.4	8.34	16.7
Bintulu	139	13.9	50.1
Miri	186	114	656

Harvesting Risk, $r_g^{Harv} \times 10^{-9}$

	D/palm	NPD/palm	PD/palm
Mukah	26.9035	231.265	8.54901
Dalat	69.8603	600.525	22.1992
Saratok	5.45857	46.9223	1.73455
Betong	10.2128	87.7901	3.24528

Processing Risk, $r_f^{Process} \times 10^{-8}$

	D/t	NPD/t	PD/t
Mukah A	2.63	38.7	4.35
Mukah B	2.63	38.7	4.35
Dalat A	3.23	47.5	5.34
Dalat B	3.23	47.5	5.34
Dalat C	3.23	47.5	5.34
Pusa	6.57	96.6	10.9

Sea freight Risk, $r^{Sea} \times 10^{-18}$

D/nmi	2210
NPD/nmi	1.0
PD/nmi	1.0

Port Handling Risk, $r_j^{Port} \times 10^{-8}$

	D/t	NPD/t	PD/t
Kuching	16.4	100	1.54
Sibu	28.2	172	2.64
Miri	24.7	151	2.31

Table A7: Emission factor of power plants and transportation, total amount of power generation, and volume of water demand of power plants

Types of Power Plant, *pp*	Amount of Power Generation,[1] PW_{pp} (MW)	Emission Factor of Power Plants,[2] EF_{pp} ($kgCO_2$/kWh)	Volume of Water Demand,[3] WR_{pp} (m^3/kWh) x 10^{-3}
Combined Cycle	317	0.702	0.684
Coal-Fired	480	1.180	0.688
Hydro	96	[4]0.041	20.016
Gas-Turbine	271	1.222	0.684
Diesoline	114	0.218	1.224
	Emission Factor of Transportation ($kgCO_2$/km-t)		
Road,[5] EF^{Fuel_Road}	0.092		
Sea,[6] EF^{Fuel_Sea}	0.011		

Data is extracted from [1]SEB (2010); [2]Shekarchian et al. (2008); [3]Okadera et al. (2014); [4]Evan et al. (2009); [5]European Environment Agency (n.d.); [6]Guidelines for measuring and managing CO_2 emission from Freight Transport Operations (n.d.).

Table A8: Power consumption of sago mills and water demand of power generation and transportation

Sago Mills	Power Consumption, $E_{f,p}$ (kWh/kg)
Mukah A	0.220
Mukah B	0.230
Dalat A	0.235
Dalat B	0.225
Dalat C	0.240
Pusa	0.218
Water Demand of Power Generation and Transportation	
Power, WR^{Power} (m^3/kWh)	0.0022
Road, WR^{Road} (m^3/kg.km) x 10^{-6}	24.334
Sea, WR^{Sea} (m^3/kg.km) x 10^{-6}	0.1005

Table A9: Total volume of inlet water and discharged wastewater, concentration and limit of discharged water

Sago Mills	Inlet Water, $F_{f,p}^{In}$ (m³/t)	Product Water Requirement, $PWR_{f,p}$ (m³/t)	Concentration of Discharged Water, $C_{f,p,b}^{Out}$ (g/m³)			
			BOD	COD	TSS	TKN
Mukah A	30.0	3.5	2900	5600	4500	83
Mukah B	35.0	5.0	4000	7000	4650	90
Dalat A	32.0	3.2	3300	6000	4200	88
Dalat B	30.5	3.5	3000	5800	4000	85
Dalat C	33.0	4.0	3500	6500	4500	92
Pusa	28.5	4.4	2650	5520	3900	80
Discharged Limit,[1] C_{b}^{Dis}			50	200	100	20

[1]*Data is extracted from DOE (n.d.).*

REFERENCES OF APPENDIX A

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APPENDIX B

LINGO FILES AND RESULTS OF CHAPTER 4

CHAPTER 4

FUZZY MULTI-FOOTPRINT OPTIMISATION (FMFO) FOR SYNTHESIS OF A SUSTAINABLE VALUE CHAIN: MALAYSIAN SAGO INDUSTRY

Coding of Case Study:

```
SETS:

PLANTATION        : YIELD, AREA, CONV_PALM_PER_TON,
CONV_LOG_PER_PALM, CAPACITY_TON, CAPACITY_PALM, CAPACITY_LOG,
PALM_PLANT,
                    UNITCOST_HARV, COST_HARV, SELLING_PROFIT_PLANT,
                    UNITRISK_HARV_D, RISK_HARV_D, UNITRISK_HARV_NPD,
RISK_HARV_NPD, UNITRISK_HARV_PD, RISK_HARV_PD,
                    UFP_H2O_ALGRI_PLANT, FP_H2O_ALGRI_PLANT,
                    TOTCFP_LUC;
RAW_MATERIAL      : TOT_QTY_RAW;
MILLS             : TOT_QTY_MILL, COST_RAW_MAT, SELLING_PROFIT_MILL,
                    UNITRISK_D_PROCESS_MILL, RISK_D_PROCESS_MILL,
UNITRISK_NPD_PROCESS_MILL, RISK_NPD_PROCESS_MILL,
UNITRISK_PD_PROCESS_MILL, RISK_PD_PROCESS_MILL;
PRODUCTS          : TOT_QTY_PRODUCT;
PORTS             : TOT_QTY_PORT, CAPACITY_PORT,
UNITCOST_HANDLING_PORT, COST_HANDLING_PORT, COST_PRODUCT_PORT,
SELLING_PROFIT_PORT,
                    UNITRISK_PORTHANDL_D, RISK_PORTHANDL_D,
UNITRISK_PORTHANDL_NPD, RISK_PORTHANDL_NPD, UNITRISK_PORTHANDL_PD,
RISK_PORTHANDL_PD;
CUSTOMERS         : TOT_QTY_CUSTOMER;
DISTRICTS         : UNITRISK_TRAN_D, UNITRISK_TRAN_NPD,
UNITRISK_TRAN_PD;
QUALITY           : DISCHARGED_LIMIT;

PLANT_RAW (PLANTATION, RAW_MATERIAL)      : MAT_PLANT_RAW,
WEIGHT_PLANT_RAW, PALM_PLANT_RAW;
RAW_MILL (RAW_MATERIAL, MILLS)            : MAT_RAW_MILL;
MILL_PROD (MILLS, PRODUCTS)               : MAT_MILL_PROD;
PROD_PORT (PRODUCTS, PORTS)               : MAT_PROD_PORT;
PORT_CUSTOMER (PORTS, CUSTOMERS)          : MAT_PORT_CUSTOMER,
CONTAINER_PORT_CUSTOMER, UNITCOST_TRAN_PORT_CUST,
COST_TRAN_PORT_CUST, SELL_PRICE_PORT_CUST,
                                            DISTANCE_PORT_CUST,
RISK_SEA_PORT_CUST_D, RISK_SEA_PORT_CUST_NPD, RISK_SEA_PORT_CUST_PD,
                                           FP_C_FUEL_SHIP_PORT_CUST,
FP_H2O_FUEL_SHIP_PORT_CUST;
PROD_CUSTOMER (PRODUCTS, CUSTOMERS)       : DEMAND_UP_CUSTOMER,
DEMAND_LOW_CUSTOMER;
```

```
PLANT_MILL (PLANTATION, MILLS)             : DISTANCE_PLANT_MILL;
MILL_PORT (MILLS, PORTS)                   : DISTANCE_MILL_PORT;

PLANT_RAW_MILL (PLANTATION, RAW_MATERIAL, MILLS)      :
MAT_PLANT_RAW_MILL, TRIP_PLANT_RAW_MILL, COST_TRAN_PLANT_MILL,
SELL_COST_PLANT_RAW_MILL,

RISK_TRAN_PL_ML_D, RISK_TRAN_PL_ML_NPD, RISK_TRAN_PL_ML_PD,

FP_C_FUEL_LORRY_PLANT_MILL, FP_H2O_FUEL_LORRY_PLANT_MILL;
RAW_MILL_PROD (RAW_MATERIAL, MILLS, PRODUCTS)         :
MAT_RAW_MILL_PROD, CONV_RAW_MILL_PROD, CAPACITY_RAW_MILL_PROD,
COST_PROCESS_MILL, UNITCOST_PROCESS_MILL,

UFP_C_POWER_RAW_MILL_PROD, ENERGY_REQ_RAW_MILL_PROD,
FP_C_POWER_RAW_MILL_PROD,
                                                       UFP_H2O_BW,
H2O_REQ_RAW_MILL_PROD, WW_OUT_RAW_MILL_PROD, FP_H2O_BW, MAX_GW,
FP_H20_GW,

UFP_H2O_POWER, FP_H2O_POWER;
MILL_PROD_PORT (MILLS, PRODUCTS, PORTS)               :
MAT_MILL_PROD_PORT, TRIP_MILL_PROD_PORT, COST_TRAN_MILL_PORT,
SELL_COST_MILL_PORT,

RISK_TRAN_ML_PORT_D, RISK_TRAN_ML_PORT_NPD, RISK_TRAN_ML_PORT_PD,

FP_C_FUEL_LORRY_MILL_PORT, FP_H2O_FUEL_LORRY_MILL_PORT;
PROD_PORT_CUST (PRODUCTS, PORTS, CUSTOMERS)           :
MAT_PROD_PORT_CUST;
PLANT_MILL_DISTRICT (PLANTATION, MILLS, DISTRICTS)    :
DIS_PLANT_MILL_DIS;
MILL_DISTRICT_PORT (PORTS, MILLS, DISTRICTS)          :
DIS_MILL_PORT_DIS;

RAW_MILL_PROD_QLY (RAW_MATERIAL, MILLS, PRODUCTS, QUALITY) :
QLT_WW_OUT_PPM, QLT_WW_OUT_KG, UFP_H2O_GW;

ENDSETS

DATA:

! SETS MEMBERS;

PLANTATION = MUKAH DALAT SARATOK BETONG;
RAW_MATERIAL = LOG;
MILLS = MUKAH_A MUKAH_B DALAT_A DALAT_B DALAT_C PUSA;
PRODUCTS = STARCH;
PORTS = KUCHING SIBU MIRI;
CUSTOMERS = JAPAN PEN_MSIA SGP THAI;
DISTRICTS = KUCH SMRH SRN SMJ SRAM BTG SRT SRK MRD SB DLT MKH TTU
BTL MR;
QUALITY = BOD COD TSS TKN;

!DATA ATTRIBUTION;

YIELD             = 22 24 18 20;     !TON/(HA.Y);
AREA              = 2599 17541 1907 3776; !HA;
CONV_PALM_PER_TON = 10 10 10 10;          !PALM/TON;
CONV_LOG_PER_PALM = 10 10 10 10;          !LOG/PALM;
```

```
WEIGHT_PLANT_RAW = 50 50 50 50;

CONV_RAW_MILL_PROD =    0.2
                        0.2
                        0.2
                        0.2
                        0.2
                        0.2;

CAPACITY_RAW_MILL_PROD = 13200
                         8250
                         7260
                         8250
                         8250
                         3960; !TON/YEAR;

!TOT_QTY_PRODUCT = 48000;

CAPACITY_PORT = 7000000
                450000
                53900; !TON/YEAR;

DEMAND_UP_CUSTOMER = 13000
                  30700
                  3000
                  1300; !TON/YEAR;

DEMAND_LOW_CUSTOMER =   12500
                        30000
                        2500
                        1000; !TON/YEAR;

CAPACITY_LORRY = 10000; !KG/TRIP;
CAPACITY_CONTAINER = 20000; !KG/CONTAINER;

UNITCOST_HARV = 3.8 4.2 3.0 3.6; !MYR/PALM;
UNITCOST_ROAD = 4.5; !MYR/KM;

DISTANCE_PLANT_MILL = 76 61 77 84 72 228
                      89 74 63 70 58 202
                      251 236 171 164 176 46
                      305 290 220 213 225 57; !KM/TRIP;

SELL_COST_PLANT_RAW_MILL = 10 10 10 10 10 10
                           12 12 12 12 12 12
                           8 8 8 8 8 8
                           9 9 9 9 9 9; !MYR/LOG;

!SELL_COST_PLANT_RAW_MILL = 10 10 12 12 12 15
                           12 12 11 11 11 14
                           15 15 14 14 14 8
                           15 15 14 14 14 9; !MYR/LOG;

DISTANCE_MILL_PORT = 514 138 414
                     499 123 400
                     429 53 358
                     422 46 365
                     434 58 353
                     289 191 574; !KM/TRIP;
```

```
UNITCOST_PROCESS_MILL = 0.108
                        0.115
                        0.117
                        0.112
                        0.122
                        0.95; ! MYR/KG;

!UNITCOST_PROCESS_MILL = 0.296
                        0.303
                        0.305
                        0.300
                        0.310
                        0.278; ! MYR/KG;

SELL_COST_MILL_PORT = 1.6 1.5 1.55
                      1.6 1.5 1.55
                      1.6 1.5 1.55
                      1.6 1.5 1.55
                      1.6 1.5 1.55
                      1.6 1.5 1.55; !MYR/KG;

!SELL_COST_MILL_PORT = 1.65 1.25 1.55
                      1.6 1.25 1.5
                      1.55 1.2 1.5
                      1.55 1.2 1.5
                      1.55 1.2 1.5
                      1.4 1.3 1.7; !MYR/KG;

UNITCOST_HANDLING_PORT = 1500
                         1300
                         1200; !MYR/CONTAINER;

UNITCOST_TRAN_PORT_CUST =  3960 1650 1485 2640
                           3729 1980 1584 2805
                           3531 2310 1650 2970; !MYR/TRIP;

SELL_PRICE_PORT_CUST = 1.9 1.6 1.7 1.8
                       1.9 1.6 1.7 1.8
                       1.9 1.6 1.7 1.8; !MYR/KG;

UNITRISK_HARV_D = 26.9035
                  69.8603
                  5.45857
                  10.2128; ! 1E-9 DEATH/PALM;

UNITRISK_TRAN_D = 0.00156
                  0.0000278
                  0.000278
                  0.0000834
                  0.00103
                  0.000278
                  0.000167
                  0.000473
                  0
                  0.00114
                  0.0000278
                  0.000278
                  0.000334
                  0.00139
```

```
                  0.00186; !1E-9 DEATH/KM;

DIS_PLANT_MILL_DIS =     0 0 0 0 0 0 0 0 0 0 0 76 0 0 0
                         0 0 0 0 0 0 0 0 0 0 0 61 0 0 0
                         0 0 0 0 0 0 0 0 0 0 63 14 0 0 0
                         0 0 0 0 0 0 0 0 0 0 70 14 0 0 0
                         0 0 0 0 0 0 0 0 0 0 58 14 0 0 0
                         0 0 0 0 0 19 27 62 28 55 23 14 0 0 0
                         0 0 0 0 0 0 0 0 0 0 13 76 0 0 0
                         0 0 0 0 0 0 0 0 0 0 13 61 0 0 0
                         0 0 0 0 0 0 0 0 0 0 63 0 0 0 0
                         0 0 0 0 0 0 0 0 0 0 70 0 0 0 0
                         0 0 0 0 0 0 0 0 0 0 58 0 0 0 0
                         0 0 0 0 0 19 27 62 28 55 11 0 0 0 0
                         0 0 0 0 0 0 7 62 28 55 23 76 0 0 0
                         0 0 0 0 0 0 7 62 28 55 23 61 0 0 0
                         0 0 0 0 0 0 12 62 28 55 14 0 0 0 0
                         0 0 0 0 0 0 12 62 28 55 7 0 0 0 0
                         0 0 0 0 0 0 12 62 28 55 19 0 0 0 0
                         0 0 0 0 0 19 27 0 0 0 0 0 0 0 0
                         0 0 0 0 0 33.4 27 62 28 55 23 76 0 0 0
                         0 0 0 0 0 33.4 27 62 28 55 23 61 0 0 0
                         0 0 0 0 0 33.4 27 62 28 55 14 0 0 0 0
                         0 0 0 0 0 33.4 27 62 28 55 7 0 0 0 0
                         0 0 0 0 0 33.4 27 62 28 55 19 0 0 0 0
                         0 0 0 0 0 56.3 0 0 0 0 0 0 0 0 0; !KM/TRIP;

UNITRISK_D_PROCESS_MILL = 0.0263
                         0.0263
                         0.0323
                         0.0323
                         0.0323
                         0.0657; ! DEATH/KG X 1E-9;

DIS_MILL_PORT_DIS =      8 12 84 18.5 110 10 27 62 28 55 23 76 0 0 0
                         8 12 84 18.5 110 10 27 62 28 55 23 61 0 0 0
                         8 12 84 18.5 110 10 27 62 28 55 14 0 0 0 0
                         8 12 84 18.5 110 10 27 62 28 55 7 0 0 0 0
                         8 12 84 18.5 110 10 27 62 28 55 19 0 0 0 0
                         8 12 84 18.5 110 56.3 0 0 0 0 0 0 0 0 0
                         0 0 0 0 0 0 0 0 0 39 23 76 0 0 0
                         0 0 0 0 0 0 0 0 0 39 23 61 0 0 0
                         0 0 0 0 0 0 0 0 0 39 14 0 0 0 0
                         0 0 0 0 0 0 0 0 0 39 7 0 0 0 0
                         0 0 0 0 0 0 0 0 0 39 19 0 0 0 0
                         0 0 0 0 0 19 27 62 28 55 0 0 0 0 0
                         0 0 0 0 0 0 0 0 0 0 0 137 34 92 151
                         0 0 0 0 0 0 0 0 0 0 0 122 34 92 151
                         0 0 0 0 0 0 0 0 0 0 9 72 34 92 151
                         0 0 0 0 0 0 0 0 0 0 16 72 34 92 151
                         0 0 0 0 0 0 0 0 0 0 4 72 34 92 151
                         0 0 0 0 0 19 27 62 28 55 24 72 34 92
151; !KM/TRIP;

UNITRISK_PORTHANDL_D =   0.164
                         0.282
                         0.247; ! DEATH/KG X 1E-9;

DISTANCE_PORT_CUST = 3321 735 540 1221
                     3135 820 625 1270
```

```
                      2968 987 792 1293; !NM/TRIP;

UNITRISK_SEA_D = 0.00000221; ! DEATH/NM X 1E-9;

UNITRISK_SEA_NPD = 0.000000001; ! DEATH/NM X 1E-9;

UNITRISK_SEA_PD = 0.000000001; ! DEATH/NM X 1E-9;

UNITRISK_HARV_NPD =      231.265
                         600.525
                         46.9223
                         87.7901; ! NPD/PALM X 1E-9;

UNITRISK_TRAN_NPD =      0.00239
                         0.000139
                         0.000195
                         0.0000278
                         0.000973
                         0.0000834
                         0.0000278
                         0.000918
                         0
                         0
                         0.000139
                         0.0000834
                         0.0000834
                         0.000139
                         0.00114; !NPD/KM X 1E-9;

UNITRISK_NPD_PROCESS_MILL =   0.387
                              0.387
                              0.475
                              0.475
                              0.475
                              0.966; !NPD/KG X 1E-9;

UNITRISK_PORTHANDL_NPD =      1
                              1.72
                              1.51; !NPD/KG X 1E-9;

UNITRISK_HARV_PD =       8.54901
                         22.1992
                         1.73455
                         3.24528; ! PD/PALM X 1E-9;

UNITRISK_TRAN_PD =       0.00234
                         0.0000278
                         0.00100
                         0.000751
                         0.0000834
                         0.000222
                         0.000584
                         0.00111
                         0
                         0.0000278
                         0.0000278
                         0.000222
                         0.000167
                         0.000501
                         0.00656; !PD/KM X 1E-9;
```

```
UNITRISK_PD_PROCESS_MILL =    0.0435
                              0.0435
                              0.0534
                              0.0534
                              0.0534
                              0.109; ! PD/KG X 1E-9;
UNITRISK_PORTHANDL_PD = 0.0154
                        0.0264
                        0.0231; ! PD/KG X 1E-9;

UFP_C_POWER_RAW_MILL_PROD = 0.8990; !kgCO2/kWh from Grid;

ENERGY_REQ_RAW_MILL_PROD = 0.220 0.230 0.235 0.225 0.240
0.218; !kWh/KG;

UFP_C_FUEL_ROAD = 0.000092; !KGCO2/KM/KG;

UFP_C_FUEL_SEA = 0.00001; !kgCO2/km.kg;

RAINFALL_REQUIRED = 2; ! M3/(M2.YEAR) @ 2000 MM/YEAR;

H2O_REQ_RAW_MILL_PROD = 30 35 32 30.5 33 28.5; !M3/TON;

WW_OUT_RAW_MILL_PROD = 26.5 30 28.8 27 29 24.1; !M3/TON;

QLT_WW_OUT_PPM =  2900 5600 4500 83
                  4000 7000 4650 90
                  3300 6000 4200 88
                  3000 5800 4000 85
                  3500 6500 4500 92
                  2650 5520 3900 80;

DISCHARGED_LIMIT = 50 200 100 20; !PPM @ G/M3;

UFP_H2O_POWER = 0.0021855; ! M3/kWh @ FROM GRID;

UFP_H2O_FUEL_ROAD = 0.000024334; ! M3/(KG.KM);

UFP_H2O_FUEL_SEA = 0.00000010051; ! M3/(KG.KM);

ENDDATA

! MASS BALANCES;

!EQ 1; @FOR(PLANTATION(G): (YIELD(G)* AREA(G))= CAPACITY_TON(G));
!EQ 2; @FOR(PLANTATION(G): (CAPACITY_TON(G)*CONV_PALM_PER_TON(G)) =
CAPACITY_PALM(G));
!EQ 3; @FOR(PLANTATION(G): (CAPACITY_PALM(G)*CONV_LOG_PER_PALM(G)) =
CAPACITY_LOG(G));
!EQ 4; @FOR(PLANTATION(G): @SUM(RAW_MATERIAL(M): MAT_PLANT_RAW(G,M))
<= CAPACITY_LOG(G));
!EQ 5; @FOR(RAW_MATERIAL(M) : @SUM(PLANTATION(G): MAT_PLANT_RAW(G,M))
= TOT_QTY_RAW(M));
!EQ 6; @FOR(RAW_MATERIAL(M) : @SUM(MILLS(F): MAT_RAW_MILL(M,F)) =
TOT_QTY_RAW(M));
!EQ 6A;@FOR(PLANT_RAW(G,M): @SUM(MILLS(F): MAT_PLANT_RAW_MILL(G,M,F))
= MAT_PLANT_RAW(G,M));
!EQ 7; @FOR(RAW_MILL(M,F) : @SUM(PLANTATION(G):
MAT_PLANT_RAW_MILL(G,M,F)) = MAT_RAW_MILL(M,F));
```

```
!EQ 7A;@FOR(MILLS(F) : @SUM(RAW_MATERIAL(M): MAT_RAW_MILL(M,F))=
TOT_QTY_MILL(F));
!EQ 8; @FOR(RAW_MILL_PROD(M,F,P) : @SUM(PLANTATION(G) :
MAT_PLANT_RAW_MILL(G,M,F)*WEIGHT_PLANT_RAW(G,M)*CONV_RAW_MILL_PROD(M
,F,P)) = MAT_RAW_MILL_PROD(M,F,P));
!EQ 9; @FOR(RAW_MILL_PROD(M,F,P) : (MAT_RAW_MILL_PROD(M,F,P))<=
CAPACITY_RAW_MILL_PROD(M,F,P)*1000);
!EQ 10;@FOR(MILL_PROD(F,P) : @SUM(RAW_MATERIAL(M):
MAT_RAW_MILL_PROD(M,F,P)) = MAT_MILL_PROD(F,P));
!EQ 10A;@FOR(MILL_PROD(F,P): @SUM(PORTS(J):
MAT_MILL_PROD_PORT(F,P,J)) = MAT_MILL_PROD(F,P));
!EQ 11;@FOR(PRODUCTS(P): @SUM(MILLS(F): MAT_MILL_PROD(F,P)) =
TOT_QTY_PRODUCT(P));
!EQ 11A;@FOR(PRODUCTS(P): @SUM(PORTS(J): MAT_PROD_PORT(P,J))=
TOT_QTY_PRODUCT(P));
!EQ 12;@FOR(PROD_PORT(P,J):@SUM(MILLS(F): MAT_MILL_PROD_PORT(F,P,J))
= MAT_PROD_PORT(P,J));
!EQ 12A;@FOR(PROD_PORT(P,J):@SUM(CUSTOMERS(U):
MAT_PROD_PORT_CUST(P,J,U)) = MAT_PROD_PORT(P,J));
!EQ 13;@FOR(PORTS(J): @SUM(PRODUCTS(P): MAT_PROD_PORT(P,J)) =
TOT_QTY_PORT(J));
!EQ 13A;@FOR(PORTS(J):@SUM(CUSTOMERS(U): MAT_PORT_CUSTOMER(J,U)) =
TOT_QTY_PORT(J));
!EQ 14;@FOR(PORTS(J):(TOT_QTY_PORT(J))<= CAPACITY_PORT(J)*1000);
!EQ 15;@FOR(PROD_CUSTOMER(P,U):@SUM(PORTS(J):
MAT_PROD_PORT_CUST(P,J,U)) <= DEMAND_UP_CUSTOMER(P,U)*1000);
!EQ 15A;@FOR(PROD_CUSTOMER(P,U):@SUM(PORTS(J):
MAT_PROD_PORT_CUST(P,J,U)) >= DEMAND_LOW_CUSTOMER(P,U)*1000);
!EQ 16;@FOR(PORT_CUSTOMER(J,U):@SUM(PRODUCTS(P):
MAT_PROD_PORT_CUST(P,J,U)) = MAT_PORT_CUSTOMER(J,U));
!EQ 17;@FOR(CUSTOMERS(U):@SUM(PORTS (J): MAT_PORT_CUSTOMER(J,U)) =
TOT_QTY_CUSTOMER(U));
!EQ 18;@FOR(PLANT_RAW_MILL(G,M,F): MAT_PLANT_RAW_MILL(G,M,F)*
WEIGHT_PLANT_RAW(G,M) / CAPACITY_LORRY <=
TRIP_PLANT_RAW_MILL(G,M,F));
@FOR(PLANT_RAW_MILL(G,M,F): @GIN(TRIP_PLANT_RAW_MILL(G,M,F)));
!EQ 19;@FOR(MILL_PROD_PORT(F,P,J):
MAT_MILL_PROD_PORT(F,P,J)/CAPACITY_LORRY <=
TRIP_MILL_PROD_PORT(F,P,J));
@FOR(MILL_PROD_PORT(F,P,J): @GIN(TRIP_MILL_PROD_PORT(F,P,J)));
!EQ 20;@FOR(PORT_CUSTOMER(J,U):
MAT_PORT_CUSTOMER(J,U)/CAPACITY_CONTAINER <=
CONTAINER_PORT_CUSTOMER(J,U));
@FOR(PORT_CUSTOMER(J,U): @GIN(CONTAINER_PORT_CUSTOMER(J,U)));
!EQ 21;@FOR(PLANT_RAW(G,M): (MAT_PLANT_RAW(G,M)/CONV_LOG_PER_PALM(G))
= PALM_PLANT_RAW(G,M));
!EQ 22;@FOR(PLANT_RAW(G,M): PALM_PLANT_RAW(G,M) <= PALM_PLANT(G));
@FOR(PLANT_RAW(G,M): @GIN(PALM_PLANT(G)));

!---------------------------------------------------------------------
---------------------------------------------------------------------
------------;

! COST COMPUTATION;

! PLANTATION;
!EQ 1; @FOR(PLANTATION(G): (UNITCOST_HARV(G)* PALM_PLANT(G)) =
COST_HARV(G));
!EQ 2; @SUM(PLANTATION(G): COST_HARV(G)) = TOTCOST_HARV;
```

```
!EQ 3; @FOR(PLANT_RAW_MILL(G,M,F): (UNITCOST_ROAD *
DISTANCE_PLANT_MILL(G,F) * TRIP_PLANT_RAW_MILL(G,M,F)) =
COST_TRAN_PLANT_MILL(G,M,F));
!EQ 4; @SUM(PLANT_RAW_MILL(G,M,F): COST_TRAN_PLANT_MILL(G,M,F)) =
TOTCOST_TRAN_PLANT_MILL;
!EQ 4A;@FOR(PLANTATION(G):
@SUM(RAW_MILL(M,F):(MAT_PLANT_RAW_MILL(G,M,F) *
SELL_COST_PLANT_RAW_MILL(G,M,F))) = SELLING_PROFIT_PLANT(G));
!EQ 4B;@SUM(PLANTATION(G): SELLING_PROFIT_PLANT(G)) = TOTSP_PLANT;
!EQ 4C;TOTNP_PLANT = TOTSP_PLANT - TOTCOST_HARV -
TOTCOST_TRAN_PLANT_MILL; @FREE(TOTNP_PLANT);

! SAGO MILLS;
!EQ 5; @FOR(MILLS(F): @SUM(PLANT_RAW(G,M): MAT_PLANT_RAW_MILL(G,M,F)
* SELL_COST_PLANT_RAW_MILL(G,M,F)) = COST_RAW_MAT(F));
!EQ 6; @SUM(MILLS(F): COST_RAW_MAT(F)) = TOTCOST_RAWMAT_MILL;
!EQ 7; @FOR(MILL_PROD_PORT(F,P,J) : (UNITCOST_ROAD *
DISTANCE_MILL_PORT(F,J) * TRIP_MILL_PROD_PORT(F,P,J)) =
COST_TRAN_MILL_PORT(F,P,J));
!EQ 8; @SUM(MILL_PROD_PORT(F,P,J) : COST_TRAN_MILL_PORT(F,P,J)) =
TOTCOST_TRAN_MILL_PORT;
!EQ 9; @FOR(RAW_MILL_PROD(M,F,P) : (UNITCOST_PROCESS_MILL(M,F,P) *
MAT_RAW_MILL_PROD(M,F,P)) = COST_PROCESS_MILL(M,F,P));
!EQ 10;@SUM(RAW_MILL_PROD(M,F,P) : COST_PROCESS_MILL(M,F,P)) =
TOTCOST_PROCESS_MILL;
!EQ 10A; @FOR(MILLS(F): @SUM(PROD_PORT(P,J):
MAT_MILL_PROD_PORT(F,P,J) * SELL_COST_MILL_PORT(F,P,J)) =
SELLING_PROFIT_MILL(F));
!EQ 10B; @SUM(MILLS(F): SELLING_PROFIT_MILL(F)) = TOTSP_MILL;
!EQ 10C; TOTNP_MILL = TOTSP_MILL - TOTCOST_RAWMAT_MILL -
TOTCOST_TRAN_MILL_PORT - TOTCOST_PROCESS_MILL; @FREE(TOTNP_MILL);

!PORTS;
!EQ 11; @FOR(PORTS(J): @SUM(CUSTOMERS(U): (UNITCOST_HANDLING_PORT(J)
* CONTAINER_PORT_CUSTOMER(J,U))) =  COST_HANDLING_PORT(J));
!EQ 12; @SUM(PORTS(J): COST_HANDLING_PORT(J)) = TOTCOST_HANDL_PORT;
!EQ 13; @FOR(PORT_CUSTOMER(J,U): (UNITCOST_TRAN_PORT_CUST(J,U) *
CONTAINER_PORT_CUSTOMER(J,U) / 3) = COST_TRAN_PORT_CUST(J,U));
!EQ 14; @SUM(PORT_CUSTOMER(J,U): COST_TRAN_PORT_CUST(J,U)) =
TOTCOST_TRAN_PORT_CUST;
!EQ 15; @FOR(PORTS(J): @SUM(MILL_PROD(F,P):
(MAT_MILL_PROD_PORT(F,P,J) * SELL_COST_MILL_PORT(F,P,J))) =
COST_PRODUCT_PORT(J));
!EQ 16; @SUM(PORTS(J): COST_PRODUCT_PORT(J)) = TOTCOST_PRODUCT_PORT;
!EQ 16A;@FOR(PORTS(J): @SUM(CUSTOMERS(U): (MAT_PORT_CUSTOMER(J,U) *
SELL_PRICE_PORT_CUST(J,U)))
 = SELLING_PROFIT_PORT(J));
!EQ 16B;@SUM(PORTS(J): SELLING_PROFIT_PORT(J)) = TOTSP_PORT;
!EQ 16C;TOTNP_PORT = TOTSP_PORT - TOTCOST_HANDL_PORT -
TOTCOST_TRAN_PORT_CUST - TOTCOST_PRODUCT_PORT; @FREE(TOTNP_PORT);

TOTCOST = TOTCOST_HARV + TOTCOST_TRAN_PLANT_MILL +
TOTCOST_RAWMAT_MILL + TOTCOST_TRAN_MILL_PORT + TOTCOST_PROCESS_MILL
+ TOTCOST_HANDL_PORT + TOTCOST_TRAN_PORT_CUST
          + TOTCOST_PRODUCT_PORT;

TOTNP = TOTNP_PLANT + TOTNP_MILL + TOTNP_PORT;

!MIN = TOTCOST;
!MAX = TOTNP;
```

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!-----------------------------------------------------------------
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! RISK COMPUTATION;

! DEATH (D) RISK;
!EQ 1; @FOR(PLANTATION(G): (PALM_PLANT(G) * UNITRISK_HARV_D(G))=
RISK_HARV_D(G));
!EQ 2; @SUM(PLANTATION(G): RISK_HARV_D(G)) = TOTRISK_HARV_D;
!EQ 3; @FOR(PLANT_RAW_MILL(G,M,F): @SUM(DISTRICTS(Y):
((UNITRISK_TRAN_D(Y) * DIS_PLANT_MILL_DIS(G,F,Y))) *
TRIP_PLANT_RAW_MILL(G,M,F)) = RISK_TRAN_PL_ML_D(G,M,F));
!EQ 4; @SUM(PLANT_RAW_MILL(G,M,F): RISK_TRAN_PL_ML_D(G,M,F)) =
TOTRISK_TRAN_PL_ML_D;
!EQ 5; @FOR(MILLS(F): @SUM(PRODUCTS(P): MAT_MILL_PROD(F,P) *
UNITRISK_D_PROCESS_MILL(F)) = RISK_D_PROCESS_MILL(F));
!EQ 6; @SUM(MILLS(F): RISK_D_PROCESS_MILL(F)) =
TOTRISK_PROCESS_MILL_D;
!EQ 7; @FOR(MILL_PROD_PORT(F,P,J):
@SUM(DISTRICTS(Y):((UNITRISK_TRAN_D(Y) * DIS_MILL_PORT_DIS(J,F,Y)))
* TRIP_MILL_PROD_PORT(F,P,J)) = RISK_TRAN_ML_PORT_D(F,P,J));
!EQ 8; @SUM(MILL_PROD_PORT(F,P,J): RISK_TRAN_ML_PORT_D(F,P,J)) =
TOTRISK_TRAN_ML_PORT_D;
!EQ 9; @FOR(PORTS(J) : (TOT_QTY_PORT(J) * UNITRISK_PORTHANDL_D(J)) =
RISK_PORTHANDL_D(J));
!EQ 10; @SUM(PORTS(J) : RISK_PORTHANDL_D(J)) = TOTRISK_PORTHANDL_D;
!EQ 11; @FOR(PORT_CUSTOMER(J,U): (DISTANCE_PORT_CUST(J,U) *
UNITRISK_SEA_D * CONTAINER_PORT_CUSTOMER(J,U)/3) =
RISK_SEA_PORT_CUST_D(J,U));
!EQ 12; @SUM(PORT_CUSTOMER(J,U): RISK_SEA_PORT_CUST_D(J,U)) =
TOTRISK_SEA_PORT_CUST_D;
!EQ 13; TOTRISK_DEATH = TOTRISK_HARV_D + TOTRISK_TRAN_PL_ML_D +
TOTRISK_PROCESS_MILL_D + TOTRISK_TRAN_ML_PORT_D +
TOTRISK_PORTHANDL_D + TOTRISK_SEA_PORT_CUST_D;

!MIN = TOTRISK_DEATH;

! NON-PERMENANT DISABILITY (NPD) RISK;
!EQ 14; @FOR(PLANTATION(G): (PALM_PLANT(G) * UNITRISK_HARV_NPD(G))=
RISK_HARV_NPD(G));
!EQ 15; @SUM(PLANTATION(G): RISK_HARV_NPD(G)) = TOTRISK_HARV_NPD;
!EQ 16; @FOR(PLANT_RAW_MILL(G,M,F): @SUM(DISTRICTS(Y):
((UNITRISK_TRAN_NPD(Y) * DIS_PLANT_MILL_DIS(G,F,Y))) *
TRIP_PLANT_RAW_MILL(G,M,F)) = RISK_TRAN_PL_ML_NPD(G,M,F));
!EQ 17; @SUM(PLANT_RAW_MILL(G,M,F): RISK_TRAN_PL_ML_NPD(G,M,F)) =
TOTRISK_TRAN_PL_ML_NPD;
!EQ 18; @FOR(MILLS(F): @SUM(PRODUCTS(P): MAT_MILL_PROD(F,P) *
UNITRISK_NPD_PROCESS_MILL(F)) = RISK_NPD_PROCESS_MILL(F));
!EQ 19; @SUM(MILLS(F): RISK_NPD_PROCESS_MILL(F)) =
TOTRISK_PROCESS_MILL_NPD;
!EQ 20; @FOR(MILL_PROD_PORT(F,P,J):
@SUM(DISTRICTS(Y):((UNITRISK_TRAN_NPD(Y) * DIS_MILL_PORT_DIS(J,F,Y)))
* TRIP_MILL_PROD_PORT(F,P,J)) = RISK_TRAN_ML_PORT_NPD(F,P,J));
!EQ 21; @SUM(MILL_PROD_PORT(F,P,J): RISK_TRAN_ML_PORT_NPD(F,P,J)) =
TOTRISK_TRAN_ML_PORT_NPD;
!EQ 22; @FOR(PORTS(J) : (TOT_QTY_PORT(J) * UNITRISK_PORTHANDL_NPD(J))
= RISK_PORTHANDL_NPD(J));
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!EQ 23; @SUM(PORTS(J) : RISK_PORTHANDL_NPD(J)) =
TOTRISK_PORTHANDL_NPD;
!EQ 23A; @FOR(PORT_CUSTOMER(J,U): (DISTANCE_PORT_CUST(J,U) *
UNITRISK_SEA_NPD * CONTAINER_PORT_CUSTOMER(J,U)/3) =
RISK_SEA_PORT_CUST_NPD(J,U));
!EQ 23B; @SUM(PORT_CUSTOMER(J,U): RISK_SEA_PORT_CUST_NPD(J,U)) =
TOTRISK_SEA_PORT_CUST_NPD;

!EQ 24; TOTRISK_NPD = TOTRISK_HARV_NPD + TOTRISK_TRAN_PL_ML_NPD +
TOTRISK_PROCESS_MILL_NPD + TOTRISK_TRAN_ML_PORT_NPD +
TOTRISK_PORTHANDL_NPD
                        + TOTRISK_SEA_PORT_CUST_NPD;

!MIN = TOTRISK_NPD;

! PERMENANT DISABILITY (PD) RISK;
!EQ 25; @FOR(PLANTATION(G): (PALM_PLANT(G) * UNITRISK_HARV_PD(G))=
RISK_HARV_PD(G));
!EQ 26; @SUM(PLANTATION(G): RISK_HARV_PD(G)) = TOTRISK_HARV_PD;
!EQ 27; @FOR(PLANT_RAW_MILL(G,M,F): @SUM(DISTRICTS(Y):
((UNITRISK_TRAN_PD(Y) * DIS_PLANT_MILL_DIS(G,F,Y))) *
TRIP_PLANT_RAW_MILL(G,M,F)) = RISK_TRAN_PL_ML_PD(G,M,F));
!EQ 28; @SUM(PLANT_RAW_MILL(G,M,F): RISK_TRAN_PL_ML_PD(G,M,F)) =
TOTRISK_TRAN_PL_ML_PD;
!EQ 29; @FOR(MILLS(F): @SUM(PRODUCTS(P): MAT_MILL_PROD(F,P) *
UNITRISK_PD_PROCESS_MILL(F)) = RISK_PD_PROCESS_MILL(F));
!EQ 30; @SUM(MILLS(F): RISK_PD_PROCESS_MILL(F)) =
TOTRISK_PROCESS_MILL_PD;
!EQ 31; @FOR(MILL_PROD_PORT(F,P,J):
@SUM(DISTRICTS(Y):((UNITRISK_TRAN_PD(Y) * DIS_MILL_PORT_DIS(J,F,Y)))
* TRIP_MILL_PROD_PORT(F,P,J)) = RISK_TRAN_ML_PORT_PD(F,P,J));
!EQ 32; @SUM(MILL_PROD_PORT(F,P,J): RISK_TRAN_ML_PORT_PD(F,P,J)) =
TOTRISK_TRAN_ML_PORT_PD;
!EQ 33; @FOR(PORTS(J) : (TOT_QTY_PORT(J) * UNITRISK_PORTHANDL_PD(J))
= RISK_PORTHANDL_PD(J));
!EQ 34; @SUM(PORTS(J) : RISK_PORTHANDL_PD(J)) = TOTRISK_PORTHANDL_PD;
!EQ 34A; @FOR(PORT_CUSTOMER(J,U): (DISTANCE_PORT_CUST(J,U) *
UNITRISK_SEA_PD * CONTAINER_PORT_CUSTOMER(J,U)/3) =
RISK_SEA_PORT_CUST_PD(J,U));
!EQ 34B; @SUM(PORT_CUSTOMER(J,U): RISK_SEA_PORT_CUST_PD(J,U)) =
TOTRISK_SEA_PORT_CUST_PD;

!EQ 35; TOTRISK_PD = TOTRISK_HARV_PD + TOTRISK_TRAN_PL_ML_PD +
TOTRISK_PROCESS_MILL_PD + TOTRISK_TRAN_ML_PORT_PD +
TOTRISK_PORTHANDL_PD + TOTRISK_SEA_PORT_CUST_PD;

!MIN = TOTRISK_PD;

!-------------------------------------------------------------------
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! CARBON FOOTPRINT;

! LUC;
@FOR(PLANTATION(G):(2.33 * AREA(G)) = TOTCFP_LUC(G));
@SUM(PLANTATION(G): TOTCFP_LUC(G)) = TOTFP_C_LUC;

! POWER GENERATION;
```

```
! EQ 1; @FOR(RAW_MILL_PROD(M,F,P):(UFP_C_POWER_RAW_MILL_PROD(M,F,P)
* ENERGY_REQ_RAW_MILL_PROD(M,F,P) * MAT_RAW_MILL_PROD(M,F,P)) =
FP_C_POWER_RAW_MILL_PROD(M,F,P));
! EQ 2; @SUM(RAW_MILL_PROD(M,F,P):FP_C_POWER_RAW_MILL_PROD(M,F,P)) =
TOTFP_C_POWER_RAW_MILL_PROD;

! FUEL CONSUMPTION;
! EQ 3; @FOR(PLANT_RAW_MILL(G,M,F):(UFP_C_FUEL_ROAD * CAPACITY_LORRY
* DISTANCE_PLANT_MILL(G,F) * TRIP_PLANT_RAW_MILL(G,M,F)) =
FP_C_FUEL_LORRY_PLANT_MILL(G,M,F));
! EQ 4; @SUM(PLANT_RAW_MILL(G,M,F):
FP_C_FUEL_LORRY_PLANT_MILL(G,M,F)) = TOTFP_C_FUEL_LORRY_PLANT_MILL;
! EQ 5; @FOR(MILL_PROD_PORT(F,P,J): (UFP_C_FUEL_ROAD *
CAPACITY_LORRY * DISTANCE_MILL_PORT(F,J) *
TRIP_MILL_PROD_PORT(F,P,J)) = FP_C_FUEL_LORRY_MILL_PORT(F,P,J));
! EQ 6; @SUM(MILL_PROD_PORT(F,P,J): FP_C_FUEL_LORRY_MILL_PORT(F,P,J))
= TOTFP_C_FUEL_LORRY_MILL_PORT;
! EQ 7; @FOR(PORT_CUSTOMER(J,U):
            (UFP_C_FUEL_SEA * 3 * CAPACITY_CONTAINER *
DISTANCE_PORT_CUST(J,U) * 1.852 * CONTAINER_PORT_CUSTOMER(J,U) / 3)
= FP_C_FUEL_SHIP_PORT_CUST(J,U));
! EQ 8; @SUM(PORT_CUSTOMER(J,U): FP_C_FUEL_SHIP_PORT_CUST(J,U)) =
TOTFP_C_FUEL_SHIP_PORT_CUST;

TOTPF_C = TOTFP_C_LUC + TOTFP_C_POWER_RAW_MILL_PROD +
TOTFP_C_FUEL_LORRY_PLANT_MILL + TOTFP_C_FUEL_LORRY_MILL_PORT +
TOTFP_C_FUEL_SHIP_PORT_CUST;

!MIN = TOTPF_C;

!---------------------------------------------------------------------
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! WATER FOOTPRINT;

! ALGRICULTURAL;
! EQ 1; @FOR(PLANTATION(G): (RAINFALL_REQUIRED / (YIELD(G) * 1000) *
10000) = UFP_H2O_ALGRI_PLANT(G));
! EQ 2; @FOR(PLANTATION(G): @SUM(RAW_MILL_PROD(M,F,P):
            (UFP_H2O_ALGRI_PLANT(G) * MAT_PLANT_RAW_MILL(G,M,F) *
WEIGHT_PLANT_RAW(G,M) * CONV_RAW_MILL_PROD(M,F,P))) =
FP_H2O_ALGRI_PLANT(G));
! EQ 3; @SUM(PLANTATION(G): FP_H2O_ALGRI_PLANT(G)) =
TOTFP_H2O_ALGRI_PLANT;

! PROCESSING;
! EQ 4; @FOR(RAW_MILL_PROD(M,F,P): (H2O_REQ_RAW_MILL_PROD(M,F,P) -
WW_OUT_RAW_MILL_PROD(M,F,P)) = UFP_H2O_BW(M,F,P));
! EQ 5; @FOR(RAW_MILL_PROD(M,F,P): (UFP_H2O_BW(M,F,P) *
MAT_RAW_MILL_PROD(M,F,P) / 1000) = FP_H2O_BW(M,F,P));
! EQ 6; @SUM(RAW_MILL_PROD(M,F,P): FP_H2O_BW(M,F,P)) = TOTFP_H2O_BW;
! EQ 7; @FOR(RAW_MILL_PROD_QLY(M,F,P,B): (QLT_WW_OUT_PPM(M,F,P,B) *
WW_OUT_RAW_MILL_PROD(M,F,P) / 1000) = QLT_WW_OUT_KG(M,F,P,B));
! EQ 8; @FOR(RAW_MILL_PROD_QLY(M,F,P,B): (QLT_WW_OUT_KG(M,F,P,B) *
1000 / DISCHARGED_LIMIT(B)) = UFP_H2O_GW(M,F,P,B));
! EQ 9; @FOR(RAW_MILL_PROD(M,F,P): @MAX(RAW_MILL_PROD_QLY(M,F,P,B):
UFP_H2O_GW(M,F,P,B)) = MAX_GW(M,F,P));
! EQ 10; @FOR(RAW_MILL_PROD(M,F,P): (MAX_GW(M,F,P) *
MAT_RAW_MILL_PROD(M,F,P) / 1000) = FP_H20_GW(M,F,P));
! EQ 11; @SUM(RAW_MILL_PROD(M,F,P): FP_H20_GW(M,F,P)) = TOTFP_H2O_GW;
```

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! POWER GENERATION;
! EQ 12; @FOR(RAW_MILL_PROD(M,F,P):
                  (UFP_H2O_POWER(M,F,P) * ENERGY_REQ_RAW_MILL_PROD
(M,F,P) * MAT_RAW_MILL_PROD(M,F,P)) = FP_H2O_POWER(M,F,P));
! EQ 13; @SUM(RAW_MILL_PROD(M,F,P): FP_H2O_POWER(M,F,P)) =
TOTFP_H2O_POWER;

! FUEL CONSUMPTION;
! EQ 14; @FOR(PLANT_RAW_MILL(G,M,F):
                  (UFP_H2O_FUEL_ROAD * CAPACITY_LORRY *
DISTANCE_PLANT_MILL(G,F) * TRIP_PLANT_RAW_MILL(G,M,F)) =
FP_H2O_FUEL_LORRY_PLANT_MILL(G,M,F));
! EQ 15; @SUM(PLANT_RAW_MILL(G,M,F):
FP_H2O_FUEL_LORRY_PLANT_MILL(G,M,F)) =
TOTFP_H2O_FUEL_LORRY_PLANT_MILL;
! EQ 16; @FOR(MILL_PROD_PORT(F,P,J):(UFP_H2O_FUEL_ROAD *
CAPACITY_LORRY * DISTANCE_MILL_PORT(F,J) *
TRIP_MILL_PROD_PORT(F,P,J)) = FP_H2O_FUEL_LORRY_MILL_PORT(F,P,J));
! EQ 17; @SUM(MILL_PROD_PORT(F,P,J):
FP_H2O_FUEL_LORRY_MILL_PORT(F,P,J))  = TOTFP_H2O_FUEL_LORRY_MILL_PORT;
! EQ 18; @FOR(PORT_CUSTOMER(J,U):
            (UFP_H2O_FUEL_SEA * 3 * CAPACITY_CONTAINER *
DISTANCE_PORT_CUST(J,U) * 1.852 * CONTAINER_PORT_CUSTOMER(J,U) / 3)
= FP_H2O_FUEL_SHIP_PORT_CUST(J,U));
! EQ 19; @SUM(PORT_CUSTOMER(J,U): FP_H2O_FUEL_SHIP_PORT_CUST(J,U)) =
TOTFP_H2O_FUEL_SHIP_PORT_CUST;


TOTFP_H2O = TOTFP_H2O_ALGRI_PLANT + TOTFP_H2O_BW + TOTFP_H2O_GW +
TOTFP_H2O_POWER + TOTFP_H2O_FUEL_LORRY_PLANT_MILL +
TOTFP_H2O_FUEL_LORRY_MILL_PORT
                  + TOTFP_H2O_FUEL_SHIP_PORT_CUST;

!MIN = TOTFP_H2O;

!-------------------------------------------------------------------
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------------;
! FUZZY OPTIMISATION;

NP_UL        = 57318690;       NP_LL        = 33410170;
D_UL         = 46616800;       D_LL         = 11997040; ! 1E-9;
NPD_UL       = 377547600;      NPD_LL       = 92707840; ! 1E-9;
PD_UL        = 13922060;       PD_LL        = 3973630; ! 1E-9;
FP_C_UL      = 17246200;       FP_C_LL      = 12900160;
FP_H2O_UL    = 136756300;      FP_H2O_LL    = 120571900;

(TOTNP - NP_LL)/(NP_UL - NP_LL)                        >= LAMDA;
(D_UL - TOTRISK_DEATH)/(D_UL - D_LL)                   >= LAMDA;
(NPD_UL - TOTRISK_NPD)/(NPD_UL - NPD_LL)               >= LAMDA;
(PD_UL - TOTRISK_PD)/(PD_UL - PD_LL)                   >= LAMDA;
(FP_C_UL - TOTPF_C)/(FP_C_UL - FP_C_LL)                >= LAMDA;
(FP_H2O_UL - TOTFP_H2O)/(FP_H2O_UL - FP_H2O_LL)        >= LAMDA;

LAMDA >= 0;
LAMDA <= 1;

MAX = LAMDA;

END
```

Results of Case Study:

```
Global optimal solution found.
Objective value:                              0.6823932
Objective bound:                              0.6823942
Infeasibilities:                              0.1836302E-07
Extended solver steps:                             1011
Total solver iterations:                           2318

Model Class:                                       MILP

Total variables:                      645
Nonlinear variables:                    0
Integer variables:                     58

Total constraints:                    634
Nonlinear constraints:                  0

Total nonzeros:                      1914
Nonlinear nonzeros:                     0
```

Variable	Value	Reduced Cost
CAPACITY_LORRY	10000.00	0.000000
CAPACITY_CONTAINER	20000.00	0.000000
UNITCOST_ROAD	4.500000	0.000000
UNITRISK_SEA_D	0.2210000E-05	0.000000
UNITRISK_SEA_NPD	0.000000	0.000000
UNITRISK_SEA_PD	0.000000	0.000000
UFP_C_FUEL_ROAD	0.9200000E-04	0.000000
UFP_C_FUEL_SEA	0.1000000E-04	0.000000
RAINFALL_REQUIRED	2.000000	0.000000
UFP_H2O_FUEL_ROAD	0.2433400E-04	0.000000
UFP_H2O_FUEL_SEA	0.1005100E-06	0.000000
TOTCOST_HARV	1687120.	0.000000
TOTCOST_TRAN_PLANT_MILL	8174835.	0.000000
TOTSP_PLANT	0.4447800E+08	0.000000
TOTNP_PLANT	0.3461604E+08	0.000000
TOTCOST_RAWMAT_MILL	0.4447800E+08	0.000000
TOTCOST_TRAN_MILL_PORT	4706379.	0.000000
TOTCOST_PROCESS_MILL	8551720.	0.000000
TOTSP_MILL	0.7089200E+08	0.000000
TOTNP_MILL	0.1315590E+08	0.000000
TOTCOST_HANDL_PORT	3179200.	0.000000
TOTCOST_TRAN_PORT_CUST	1775565.	0.000000
TOTCOST_PRODUCT_PORT	0.7089200E+08	0.000000
TOTSP_PORT	0.7780000E+08	0.000000
TOTNP_PORT	1953235.	0.000000
TOTCOST	0.1434448E+09	0.000000
TOTNP	0.4972518E+08	0.000000
TOTRISK_HARV_D	0.1074365E+08	0.000000
TOTRISK_TRAN_PL_ML_D	430.4828	0.000000
TOTRISK_PROCESS_MILL_D	1508384.	0.000000
TOTRISK_TRAN_ML_PORT_D	599.4303	0.000000
TOTRISK_PORTHANDL_D	0.1073944E+08	0.000000
TOTRISK_SEA_PORT_CUST_D	2.394601	0.000000
TOTRISK_DEATH	0.2299251E+08	0.000000
TOTRISK_HARV_NPD	0.9235342E+08	0.000000
TOTRISK_TRAN_PL_ML_NPD	264.7983	0.000000
TOTRISK_PROCESS_MILL_NPD	0.2218572E+08	0.000000

TOTRISK_TRAN_ML_PORT_NPD	384.3615	0.000000
TOTRISK_PORTHANDL_NPD	0.6549760E+08	0.000000
TOTRISK_SEA_PORT_CUST_NPD	0.1083530E-02	0.000000
TOTRISK_NPD	0.1800374E+09	0.000000
TOTRISK_HARV_PD	3413964.	0.000000
TOTRISK_TRAN_PL_ML_PD	375.5913	0.000000
TOTRISK_PROCESS_MILL_PD	2495604.	0.000000
TOTRISK_TRAN_ML_PORT_PD	409.8568	0.000000
TOTRISK_PORTHANDL_PD	1006280.	0.000000
TOTRISK_SEA_PORT_CUST_PD	0.1083530E-02	0.000000
TOTRISK_PD	6916634.	0.000000
TOTFP_C_LUC	60167.59	0.000000
TOTFP_C_POWER_RAW_MILL_PROD	9419749.	0.000000
TOTFP_C_FUEL_LORRY_PLANT_MILL	1671300.	0.000000
TOTFP_C_FUEL_LORRY_MILL_PORT	962193.0	0.000000
TOTFP_C_FUEL_SHIP_PORT_CUST	1204019.	0.000000
TOTPF_C	0.1331743E+08	0.000000
TOTFP_H2O_ALGRI_PLANT	0.4335556E+08	0.000000
TOTFP_H2O_BW	174131.0	0.000000
TOTFP_H2O_GW	0.8145082E+08	0.000000
TOTFP_H2O_POWER	22899.73	0.000000
TOTFP_H2O_FUEL_LORRY_PLANT_MILL	442058.7	0.000000
TOTFP_H2O_FUEL_LORRY_MILL_PORT	254500.1	0.000000
TOTFP_H2O_FUEL_SHIP_PORT_CUST	12101.59	0.000000
TOTFP_H2O	0.1257121E+09	0.000000
NP_UL	0.5731869E+08	0.000000
NP_LL	0.3341017E+08	0.000000
D_UL	0.4661680E+08	0.000000
D_LL	0.1199704E+08	0.000000
NPD_UL	0.3775476E+09	0.000000
NPD_LL	0.9270784E+08	0.000000
PD_UL	0.1392206E+08	0.000000
PD_LL	3973630.	0.000000
FP_C_UL	0.1724620E+08	0.000000
FP_C_LL	0.1290016E+08	0.000000
FP_H2O_UL	0.1367563E+09	0.000000
FP_H2O_LL	0.1205719E+09	0.000000
LAMDA	0.6823932	0.000000
YIELD(MUKAH)	22.00000	0.000000
YIELD(DALAT)	24.00000	0.000000
YIELD(SARATOK)	18.00000	0.000000
YIELD(BETONG)	20.00000	0.000000
AREA(MUKAH)	2599.000	0.000000
AREA(DALAT)	17541.00	0.000000
AREA(SARATOK)	1907.000	0.000000
AREA(BETONG)	3776.000	0.000000
CONV_PALM_PER_TON(MUKAH)	10.00000	0.000000
CONV_PALM_PER_TON(DALAT)	10.00000	0.000000
CONV_PALM_PER_TON(SARATOK)	10.00000	0.000000
CONV_PALM_PER_TON(BETONG)	10.00000	0.000000
CONV_LOG_PER_PALM(MUKAH)	10.00000	0.000000
CONV_LOG_PER_PALM(DALAT)	10.00000	0.000000
CONV_LOG_PER_PALM(SARATOK)	10.00000	0.000000
CONV_LOG_PER_PALM(BETONG)	10.00000	0.000000
CAPACITY_TON(MUKAH)	57178.00	0.000000
CAPACITY_TON(DALAT)	420984.0	0.000000
CAPACITY_TON(SARATOK)	34326.00	0.000000
CAPACITY_TON(BETONG)	75520.00	0.000000
CAPACITY_PALM(MUKAH)	571780.0	0.000000
CAPACITY_PALM(DALAT)	4209840.	0.000000

CAPACITY_PALM(SARATOK)	343260.0	0.000000
CAPACITY_PALM(BETONG)	755200.0	0.000000
CAPACITY_LOG(MUKAH)	5717800.	0.000000
CAPACITY_LOG(DALAT)	0.4209840E+08	0.000000
CAPACITY_LOG(SARATOK)	3432600.	0.000000
CAPACITY_LOG(BETONG)	7552000.	0.000000
PALM_PLANT(MUKAH)	383900.0	0.1589392E-06
PALM_PLANT(DALAT)	0.000000	0.1756696E-06
PALM_PLANT(SARATOK)	76100.00	0.1254783E-06
PALM_PLANT(BETONG)	0.000000	0.1505739E-06
UNITCOST_HARV(MUKAH)	3.800000	0.000000
UNITCOST_HARV(DALAT)	4.200000	0.000000
UNITCOST_HARV(SARATOK)	3.000000	0.000000
UNITCOST_HARV(BETONG)	3.600000	0.000000
COST_HARV(MUKAH)	1458820.	0.000000
COST_HARV(DALAT)	0.000000	0.000000
COST_HARV(SARATOK)	228300.0	0.000000
COST_HARV(BETONG)	0.000000	0.000000
SELLING_PROFIT_PLANT(MUKAH)	0.3839000E+08	0.000000
SELLING_PROFIT_PLANT(DALAT)	0.000000	0.000000
SELLING_PROFIT_PLANT(SARATOK)	6088000.	0.000000
SELLING_PROFIT_PLANT(BETONG)	0.000000	0.000000
UNITRISK_HARV_D(MUKAH)	26.90350	0.000000
UNITRISK_HARV_D(DALAT)	69.86030	0.000000
UNITRISK_HARV_D(SARATOK)	5.458570	0.000000
UNITRISK_HARV_D(BETONG)	10.21280	0.000000
RISK_HARV_D(MUKAH)	0.1032825E+08	0.000000
RISK_HARV_D(DALAT)	0.000000	0.000000
RISK_HARV_D(SARATOK)	415397.2	0.000000
RISK_HARV_D(BETONG)	0.000000	0.000000
UNITRISK_HARV_NPD(MUKAH)	231.2650	0.000000
UNITRISK_HARV_NPD(DALAT)	600.5250	0.000000
UNITRISK_HARV_NPD(SARATOK)	46.92230	0.000000
UNITRISK_HARV_NPD(BETONG)	87.79010	0.000000
RISK_HARV_NPD(MUKAH)	0.8878263E+08	0.000000
RISK_HARV_NPD(DALAT)	0.000000	0.000000
RISK_HARV_NPD(SARATOK)	3570787.	0.000000
RISK_HARV_NPD(BETONG)	0.000000	0.000000
UNITRISK_HARV_PD(MUKAH)	8.549010	0.000000
UNITRISK_HARV_PD(DALAT)	22.19920	0.000000
UNITRISK_HARV_PD(SARATOK)	1.734550	0.000000
UNITRISK_HARV_PD(BETONG)	3.245280	0.000000
RISK_HARV_PD(MUKAH)	3281965.	0.000000
RISK_HARV_PD(DALAT)	0.000000	0.000000
RISK_HARV_PD(SARATOK)	131999.3	0.000000
RISK_HARV_PD(BETONG)	0.000000	0.000000
UFP_H2O_ALGRI_PLANT(MUKAH)	0.9090909	0.000000
UFP_H2O_ALGRI_PLANT(DALAT)	0.8333333	0.000000
UFP_H2O_ALGRI_PLANT(SARATOK)	1.111111	0.000000
UFP_H2O_ALGRI_PLANT(BETONG)	1.000000	0.000000
FP_H2O_ALGRI_PLANT(MUKAH)	0.3490000E+08	0.000000
FP_H2O_ALGRI_PLANT(DALAT)	0.000000	0.000000
FP_H2O_ALGRI_PLANT(SARATOK)	8455556.	0.000000
FP_H2O_ALGRI_PLANT(BETONG)	0.000000	0.000000
TOTCFP_LUC(MUKAH)	6055.670	0.000000
TOTCFP_LUC(DALAT)	40870.53	0.000000
TOTCFP_LUC(SARATOK)	4443.310	0.000000
TOTCFP_LUC(BETONG)	8798.080	0.000000
TOT_QTY_RAW(LOG)	4600000.	0.000000
TOT_QTY_MILL(MUKAH_A)	1320000.	0.000000

TOT_QTY_MILL(MUKAH_B)	508000.0	0.000000
TOT_QTY_MILL(DALAT_A)	726000.0	0.000000
TOT_QTY_MILL(DALAT_B)	825000.0	0.000000
TOT_QTY_MILL(DALAT_C)	825000.0	0.000000
TOT_QTY_MILL(PUSA)	396000.0	0.000000
COST_RAW_MAT(MUKAH_A)	0.1320000E+08	0.000000
COST_RAW_MAT(MUKAH_B)	5080000.	0.000000
COST_RAW_MAT(DALAT_A)	7260000.	0.000000
COST_RAW_MAT(DALAT_B)	7520000.	0.000000
COST_RAW_MAT(DALAT_C)	8250000.	0.000000
COST_RAW_MAT(PUSA)	3168000.	0.000000
SELLING_PROFIT_MILL(MUKAH_A)	0.2047100E+08	0.000000
SELLING_PROFIT_MILL(MUKAH_B)	7620000.	0.000000
SELLING_PROFIT_MILL(DALAT_A)	0.1089000E+08	0.000000
SELLING_PROFIT_MILL(DALAT_B)	0.1237500E+08	0.000000
SELLING_PROFIT_MILL(DALAT_C)	0.1320000E+08	0.000000
SELLING_PROFIT_MILL(PUSA)	6336000.	0.000000
UNITRISK_D_PROCESS_MILL(MUKAH_A)	0.2630000E-01	0.000000
UNITRISK_D_PROCESS_MILL(MUKAH_B)	0.2630000E-01	0.000000
UNITRISK_D_PROCESS_MILL(DALAT_A)	0.3230000E-01	0.000000
UNITRISK_D_PROCESS_MILL(DALAT_B)	0.3230000E-01	0.000000
UNITRISK_D_PROCESS_MILL(DALAT_C)	0.3230000E-01	0.000000
UNITRISK_D_PROCESS_MILL(PUSA)	0.6570000E-01	0.000000
RISK_D_PROCESS_MILL(MUKAH_A)	347160.0	0.000000
RISK_D_PROCESS_MILL(MUKAH_B)	133604.0	0.000000
RISK_D_PROCESS_MILL(DALAT_A)	234498.0	0.000000
RISK_D_PROCESS_MILL(DALAT_B)	266475.0	0.000000
RISK_D_PROCESS_MILL(DALAT_C)	266475.0	0.000000
RISK_D_PROCESS_MILL(PUSA)	260172.0	0.000000
UNITRISK_NPD_PROCESS_MILL(MUKAH_A)	0.3870000	0.000000
UNITRISK_NPD_PROCESS_MILL(MUKAH_B)	0.3870000	0.000000
UNITRISK_NPD_PROCESS_MILL(DALAT_A)	0.4750000	0.000000
UNITRISK_NPD_PROCESS_MILL(DALAT_B)	0.4750000	0.000000
UNITRISK_NPD_PROCESS_MILL(DALAT_C)	0.4750000	0.000000
UNITRISK_NPD_PROCESS_MILL(PUSA)	0.9660000	0.000000
RISK_NPD_PROCESS_MILL(MUKAH_A)	5108400.	0.000000
RISK_NPD_PROCESS_MILL(MUKAH_B)	1965960.	0.000000
RISK_NPD_PROCESS_MILL(DALAT_A)	3448500.	0.000000
RISK_NPD_PROCESS_MILL(DALAT_B)	3918750.	0.000000
RISK_NPD_PROCESS_MILL(DALAT_C)	3918750.	0.000000
RISK_NPD_PROCESS_MILL(PUSA)	3825360.	0.000000
UNITRISK_PD_PROCESS_MILL(MUKAH_A)	0.4350000E-01	0.000000
UNITRISK_PD_PROCESS_MILL(MUKAH_B)	0.4350000E-01	0.000000
UNITRISK_PD_PROCESS_MILL(DALAT_A)	0.5340000E-01	0.000000
UNITRISK_PD_PROCESS_MILL(DALAT_B)	0.5340000E-01	0.000000
UNITRISK_PD_PROCESS_MILL(DALAT_C)	0.5340000E-01	0.000000
UNITRISK_PD_PROCESS_MILL(PUSA)	0.1090000	0.000000
RISK_PD_PROCESS_MILL(MUKAH_A)	574200.0	0.000000
RISK_PD_PROCESS_MILL(MUKAH_B)	220980.0	0.000000
RISK_PD_PROCESS_MILL(DALAT_A)	387684.0	0.000000
RISK_PD_PROCESS_MILL(DALAT_B)	440550.0	0.000000
RISK_PD_PROCESS_MILL(DALAT_C)	440550.0	0.000000
RISK_PD_PROCESS_MILL(PUSA)	431640.0	0.000000
TOT_QTY_PRODUCT(STARCH)	0.4600000E+08	0.000000
TOT_QTY_PORT(KUCHING)	0.1892000E+08	0.000000
TOT_QTY_PORT(SIBU)	0.2708000E+08	0.000000
TOT_QTY_PORT(MIRI)	0.000000	0.000000
CAPACITY_PORT(KUCHING)	7000000.	0.000000
CAPACITY_PORT(SIBU)	450000.0	0.000000
CAPACITY_PORT(MIRI)	53900.00	0.000000

UNITCOST_HANDLING_PORT(KUCHING)	1500.000	0.000000
UNITCOST_HANDLING_PORT(SIBU)	1300.000	0.000000
UNITCOST_HANDLING_PORT(MIRI)	1200.000	0.000000
COST_HANDLING_PORT(KUCHING)	1419000.	0.000000
COST_HANDLING_PORT(SIBU)	1760200.	0.000000
COST_HANDLING_PORT(MIRI)	0.000000	0.000000
COST_PRODUCT_PORT(KUCHING)	0.3027200E+08	0.000000
COST_PRODUCT_PORT(SIBU)	0.4062000E+08	0.000000
COST_PRODUCT_PORT(MIRI)	0.000000	0.000000
SELLING_PROFIT_PORT(KUCHING)	0.3027200E+08	0.000000
SELLING_PROFIT_PORT(SIBU)	0.4752800E+08	0.000000
SELLING_PROFIT_PORT(MIRI)	0.000000	0.000000
UNITRISK_PORTHANDL_D(KUCHING)	0.1640000	0.000000
UNITRISK_PORTHANDL_D(SIBU)	0.2820000	0.000000
UNITRISK_PORTHANDL_D(MIRI)	0.2470000	0.000000
RISK_PORTHANDL_D(KUCHING)	3102880.	0.000000
RISK_PORTHANDL_D(SIBU)	7636560.	0.000000
RISK_PORTHANDL_D(MIRI)	0.000000	0.000000
UNITRISK_PORTHANDL_NPD(KUCHING)	1.000000	0.000000
UNITRISK_PORTHANDL_NPD(SIBU)	1.720000	0.000000
UNITRISK_PORTHANDL_NPD(MIRI)	1.510000	0.000000
RISK_PORTHANDL_NPD(KUCHING)	0.1892000E+08	0.000000
RISK_PORTHANDL_NPD(SIBU)	0.4657760E+08	0.000000
RISK_PORTHANDL_NPD(MIRI)	0.000000	0.000000
UNITRISK_PORTHANDL_PD(KUCHING)	0.1540000E-01	0.000000
UNITRISK_PORTHANDL_PD(SIBU)	0.2640000E-01	0.000000
UNITRISK_PORTHANDL_PD(MIRI)	0.2310000E-01	0.000000
RISK_PORTHANDL_PD(KUCHING)	291368.0	0.000000
RISK_PORTHANDL_PD(SIBU)	714912.0	0.000000
RISK_PORTHANDL_PD(MIRI)	0.000000	0.000000
TOT_QTY_CUSTOMER(JAPAN)	0.1250000E+08	0.000000
TOT_QTY_CUSTOMER(PEN_MSIA)	0.3000000E+08	0.000000
TOT_QTY_CUSTOMER(SGP)	2500000.	0.000000
TOT_QTY_CUSTOMER(THAI)	1000000.	0.000000
UNITRISK_TRAN_D(KUCH)	0.1560000E-02	0.000000
UNITRISK_TRAN_D(SMRH)	0.2780000E-04	0.000000
UNITRISK_TRAN_D(SRN)	0.2780000E-03	0.000000
UNITRISK_TRAN_D(SMJ)	0.8340000E-04	0.000000
UNITRISK_TRAN_D(SRAM)	0.1030000E-02	0.000000
UNITRISK_TRAN_D(BTG)	0.2780000E-03	0.000000
UNITRISK_TRAN_D(SRT)	0.1670000E-03	0.000000
UNITRISK_TRAN_D(SRK)	0.4730000E-03	0.000000
UNITRISK_TRAN_D(MRD)	0.000000	0.000000
UNITRISK_TRAN_D(SB)	0.1140000E-02	0.000000
UNITRISK_TRAN_D(DLT)	0.2780000E-04	0.000000
UNITRISK_TRAN_D(MKH)	0.2780000E-03	0.000000
UNITRISK_TRAN_D(TTU)	0.3340000E-03	0.000000
UNITRISK_TRAN_D(BTL)	0.1390000E-02	0.000000
UNITRISK_TRAN_D(MR)	0.1860000E-02	0.000000
UNITRISK_TRAN_NPD(KUCH)	0.2390000E-02	0.000000
UNITRISK_TRAN_NPD(SMRH)	0.1390000E-03	0.000000
UNITRISK_TRAN_NPD(SRN)	0.1950000E-03	0.000000
UNITRISK_TRAN_NPD(SMJ)	0.2780000E-04	0.000000
UNITRISK_TRAN_NPD(SRAM)	0.9730000E-03	0.000000
UNITRISK_TRAN_NPD(BTG)	0.8340000E-04	0.000000
UNITRISK_TRAN_NPD(SRT)	0.2780000E-04	0.000000
UNITRISK_TRAN_NPD(SRK)	0.9180000E-03	0.000000
UNITRISK_TRAN_NPD(MRD)	0.000000	0.000000
UNITRISK_TRAN_NPD(SB)	0.000000	0.000000
UNITRISK_TRAN_NPD(DLT)	0.1390000E-03	0.000000

UNITRISK_TRAN_NPD(MKH)	0.8340000E-04	0.000000
UNITRISK_TRAN_NPD(TTU)	0.8340000E-04	0.000000
UNITRISK_TRAN_NPD(BTL)	0.1390000E-03	0.000000
UNITRISK_TRAN_NPD(MR)	0.1140000E-02	0.000000
UNITRISK_TRAN_PD(KUCH)	0.2340000E-02	0.000000
UNITRISK_TRAN_PD(SMRH)	0.2780000E-04	0.000000
UNITRISK_TRAN_PD(SRN)	0.1000000E-02	0.000000
UNITRISK_TRAN_PD(SMJ)	0.7510000E-03	0.000000
UNITRISK_TRAN_PD(SRAM)	0.8340000E-04	0.000000
UNITRISK_TRAN_PD(BTG)	0.2220000E-03	0.000000
UNITRISK_TRAN_PD(SRT)	0.5840000E-03	0.000000
UNITRISK_TRAN_PD(SRK)	0.1110000E-02	0.000000
UNITRISK_TRAN_PD(MRD)	0.000000	0.000000
UNITRISK_TRAN_PD(SB)	0.2780000E-04	0.000000
UNITRISK_TRAN_PD(DLT)	0.2780000E-04	0.000000
UNITRISK_TRAN_PD(MKH)	0.2220000E-03	0.000000
UNITRISK_TRAN_PD(TTU)	0.1670000E-03	0.000000
UNITRISK_TRAN_PD(BTL)	0.5010000E-03	0.000000
UNITRISK_TRAN_PD(MR)	0.6560000E-02	0.000000
DISCHARGED_LIMIT(BOD)	50.00000	0.000000
DISCHARGED_LIMIT(COD)	200.0000	0.000000
DISCHARGED_LIMIT(TSS)	100.0000	0.000000
DISCHARGED_LIMIT(TKN)	20.00000	0.000000
MAT_PLANT_RAW(MUKAH, LOG)	3839000.	0.000000
MAT_PLANT_RAW(DALAT, LOG)	0.000000	0.000000
MAT_PLANT_RAW(SARATOK, LOG)	761000.0	0.000000
MAT_PLANT_RAW(BETONG, LOG)	0.000000	0.000000
WEIGHT_PLANT_RAW(MUKAH, LOG)	50.00000	0.000000
WEIGHT_PLANT_RAW(DALAT, LOG)	50.00000	0.000000
WEIGHT_PLANT_RAW(SARATOK, LOG)	50.00000	0.000000
WEIGHT_PLANT_RAW(BETONG, LOG)	50.00000	0.000000
PALM_PLANT_RAW(MUKAH, LOG)	383900.0	0.000000
PALM_PLANT_RAW(DALAT, LOG)	0.000000	0.000000
PALM_PLANT_RAW(SARATOK, LOG)	76100.00	0.000000
PALM_PLANT_RAW(BETONG, LOG)	0.000000	0.000000
MAT_RAW_MILL(LOG, MUKAH_A)	1320000.	0.000000
MAT_RAW_MILL(LOG, MUKAH_B)	508000.0	0.000000
MAT_RAW_MILL(LOG, DALAT_A)	726000.0	0.000000
MAT_RAW_MILL(LOG, DALAT_B)	825000.0	0.000000
MAT_RAW_MILL(LOG, DALAT_C)	825000.0	0.000000
MAT_RAW_MILL(LOG, PUSA)	396000.0	0.000000
MAT_MILL_PROD(MUKAH_A, STARCH)	0.1320000E+08	0.000000
MAT_MILL_PROD(MUKAH_B, STARCH)	5080000.	0.000000
MAT_MILL_PROD(DALAT_A, STARCH)	7260000.	0.000000
MAT_MILL_PROD(DALAT_B, STARCH)	8250000.	0.000000
MAT_MILL_PROD(DALAT_C, STARCH)	8250000.	0.000000
MAT_MILL_PROD(PUSA, STARCH)	3960000.	0.000000
MAT_PROD_PORT(STARCH, KUCHING)	0.1892000E+08	0.000000
MAT_PROD_PORT(STARCH, SIBU)	0.2708000E+08	0.000000
MAT_PROD_PORT(STARCH, MIRI)	0.000000	0.000000
MAT_PORT_CUSTOMER(KUCHING, JAPAN)	0.000000	0.000000
MAT_PORT_CUSTOMER(KUCHING, PEN_MSIA)	0.1892000E+08	0.000000
MAT_PORT_CUSTOMER(KUCHING, SGP)	0.000000	0.000000
MAT_PORT_CUSTOMER(KUCHING, THAI)	0.000000	0.000000
MAT_PORT_CUSTOMER(SIBU, JAPAN)	0.1250000E+08	0.000000
MAT_PORT_CUSTOMER(SIBU, PEN_MSIA)	0.1108000E+08	0.000000
MAT_PORT_CUSTOMER(SIBU, SGP)	2500000.	0.000000
MAT_PORT_CUSTOMER(SIBU, THAI)	1000000.	0.000000
MAT_PORT_CUSTOMER(MIRI, JAPAN)	0.000000	0.000000
MAT_PORT_CUSTOMER(MIRI, PEN_MSIA)	0.000000	0.000000

MAT_PORT_CUSTOMER(MIRI, SGP)	0.000000	0.000000
MAT_PORT_CUSTOMER(MIRI, THAI)	0.000000	0.000000
CONTAINER_PORT_CUSTOMER(KUCHING, JAPAN	0.000000	-0.6767462E-03
CONTAINER_PORT_CUSTOMER(KUCHING, PEN_M	946.0000	-0.4579957E-03
CONTAINER_PORT_CUSTOMER(KUCHING, SGP)	0.000000	-0.5439483E-03
CONTAINER_PORT_CUSTOMER(KUCHING, THAI)	0.000000	-0.6114975E-03
CONTAINER_PORT_CUSTOMER(SIBU, JAPAN)	625.0000	-0.1385155E-02
CONTAINER_PORT_CUSTOMER(SIBU, PEN_MSIA	554.0000	-0.1158583E-02
CONTAINER_PORT_CUSTOMER(SIBU, SGP)	125.0000	-0.1247756E-02
CONTAINER_PORT_CUSTOMER(SIBU, THAI)	50.00000	-0.1314385E-02
CONTAINER_PORT_CUSTOMER(MIRI, JAPAN)	0.000000	-0.1489971E-02
CONTAINER_PORT_CUSTOMER(MIRI, PEN_MSIA	0.000000	-0.1256038E-02
CONTAINER_PORT_CUSTOMER(MIRI, SGP)	0.000000	-0.1348892E-02
CONTAINER_PORT_CUSTOMER(MIRI, THAI)	0.000000	-0.1414140E-02
UNITCOST_TRAN_PORT_CUST(KUCHING, JAPAN	3960.000	0.000000
UNITCOST_TRAN_PORT_CUST(KUCHING, PEN_M	1650.000	0.000000
UNITCOST_TRAN_PORT_CUST(KUCHING, SGP)	1485.000	0.000000
UNITCOST_TRAN_PORT_CUST(KUCHING, THAI)	2640.000	0.000000
UNITCOST_TRAN_PORT_CUST(SIBU, JAPAN)	3729.000	0.000000
UNITCOST_TRAN_PORT_CUST(SIBU, PEN_MSIA	1980.000	0.000000
UNITCOST_TRAN_PORT_CUST(SIBU, SGP)	1584.000	0.000000
UNITCOST_TRAN_PORT_CUST(SIBU, THAI)	2805.000	0.000000
UNITCOST_TRAN_PORT_CUST(MIRI, JAPAN)	3531.000	0.000000
UNITCOST_TRAN_PORT_CUST(MIRI, PEN_MSIA	2310.000	0.000000
UNITCOST_TRAN_PORT_CUST(MIRI, SGP)	1650.000	0.000000
UNITCOST_TRAN_PORT_CUST(MIRI, THAI)	2970.000	0.000000
COST_TRAN_PORT_CUST(KUCHING, JAPAN)	0.000000	0.000000
COST_TRAN_PORT_CUST(KUCHING, PEN_MSIA)	520300.0	0.000000
COST_TRAN_PORT_CUST(KUCHING, SGP)	0.000000	0.000000
COST_TRAN_PORT_CUST(KUCHING, THAI)	0.000000	0.000000
COST_TRAN_PORT_CUST(SIBU, JAPAN)	776875.0	0.000000
COST_TRAN_PORT_CUST(SIBU, PEN_MSIA)	365640.0	0.000000
COST_TRAN_PORT_CUST(SIBU, SGP)	66000.00	0.000000
COST_TRAN_PORT_CUST(SIBU, THAI)	46750.00	0.000000
COST_TRAN_PORT_CUST(MIRI, JAPAN)	0.000000	0.000000
COST_TRAN_PORT_CUST(MIRI, PEN_MSIA)	0.000000	0.000000
COST_TRAN_PORT_CUST(MIRI, SGP)	0.000000	0.000000
COST_TRAN_PORT_CUST(MIRI, THAI)	0.000000	0.000000
SELL_PRICE_PORT_CUST(KUCHING, JAPAN)	1.900000	0.000000
SELL_PRICE_PORT_CUST(KUCHING, PEN_MSIA	1.600000	0.000000
SELL_PRICE_PORT_CUST(KUCHING, SGP)	1.700000	0.000000
SELL_PRICE_PORT_CUST(KUCHING, THAI)	1.800000	0.000000
SELL_PRICE_PORT_CUST(SIBU, JAPAN)	1.900000	0.000000
SELL_PRICE_PORT_CUST(SIBU, PEN_MSIA)	1.600000	0.000000
SELL_PRICE_PORT_CUST(SIBU, SGP)	1.700000	0.000000
SELL_PRICE_PORT_CUST(SIBU, THAI)	1.800000	0.000000
SELL_PRICE_PORT_CUST(MIRI, JAPAN)	1.900000	0.000000
SELL_PRICE_PORT_CUST(MIRI, PEN_MSIA)	1.600000	0.000000
SELL_PRICE_PORT_CUST(MIRI, SGP)	1.700000	0.000000
SELL_PRICE_PORT_CUST(MIRI, THAI)	1.800000	0.000000
DISTANCE_PORT_CUST(KUCHING, JAPAN)	3321.000	0.000000
DISTANCE_PORT_CUST(KUCHING, PEN_MSIA)	735.0000	0.000000
DISTANCE_PORT_CUST(KUCHING, SGP)	540.0000	0.000000
DISTANCE_PORT_CUST(KUCHING, THAI)	1221.000	0.000000
DISTANCE_PORT_CUST(SIBU, JAPAN)	3135.000	0.000000
DISTANCE_PORT_CUST(SIBU, PEN_MSIA)	820.0000	0.000000
DISTANCE_PORT_CUST(SIBU, SGP)	625.0000	0.000000
DISTANCE_PORT_CUST(SIBU, THAI)	1270.000	0.000000
DISTANCE_PORT_CUST(MIRI, JAPAN)	2968.000	0.000000
DISTANCE_PORT_CUST(MIRI, PEN_MSIA)	987.0000	0.000000

DISTANCE_PORT_CUST(MIRI, SGP)	792.0000	0.000000
DISTANCE_PORT_CUST(MIRI, THAI)	1293.000	0.000000
RISK_SEA_PORT_CUST_D(KUCHING, JAPAN)	0.000000	0.000000
RISK_SEA_PORT_CUST_D(KUCHING, PEN_MSIA	0.5122117	0.000000
RISK_SEA_PORT_CUST_D(KUCHING, SGP)	0.000000	0.000000
RISK_SEA_PORT_CUST_D(KUCHING, THAI)	0.000000	0.000000
RISK_SEA_PORT_CUST_D(SIBU, JAPAN)	1.443406	0.000000
RISK_SEA_PORT_CUST_D(SIBU, PEN_MSIA)	0.3346529	0.000000
RISK_SEA_PORT_CUST_D(SIBU, SGP)	0.5755208E-01	0.000000
RISK_SEA_PORT_CUST_D(SIBU, THAI)	0.4677833E-01	0.000000
RISK_SEA_PORT_CUST_D(MIRI, JAPAN)	0.000000	0.000000
RISK_SEA_PORT_CUST_D(MIRI, PEN_MSIA)	0.000000	0.000000
RISK_SEA_PORT_CUST_D(MIRI, SGP)	0.000000	0.000000
RISK_SEA_PORT_CUST_D(MIRI, THAI)	0.000000	0.000000
RISK_SEA_PORT_CUST_NPD(KUCHING, JAPAN)	0.000000	0.000000
RISK_SEA_PORT_CUST_NPD(KUCHING, PEN_MS	0.2317700E-03	0.000000
RISK_SEA_PORT_CUST_NPD(KUCHING, SGP)	0.000000	0.000000
RISK_SEA_PORT_CUST_NPD(KUCHING, THAI)	0.000000	0.000000
RISK_SEA_PORT_CUST_NPD(SIBU, JAPAN)	0.6531250E-03	0.000000
RISK_SEA_PORT_CUST_NPD(SIBU, PEN_MSIA)	0.1514267E-03	0.000000
RISK_SEA_PORT_CUST_NPD(SIBU, SGP)	0.2604167E-04	0.000000
RISK_SEA_PORT_CUST_NPD(SIBU, THAI)	0.2116667E-04	0.000000
RISK_SEA_PORT_CUST_NPD(MIRI, JAPAN)	0.000000	0.000000
RISK_SEA_PORT_CUST_NPD(MIRI, PEN_MSIA)	0.000000	0.000000
RISK_SEA_PORT_CUST_NPD(MIRI, SGP)	0.000000	0.000000
RISK_SEA_PORT_CUST_NPD(MIRI, THAI)	0.000000	0.000000
RISK_SEA_PORT_CUST_PD(KUCHING, JAPAN)	0.000000	0.000000
RISK_SEA_PORT_CUST_PD(KUCHING, PEN_MSI	0.2317700E-03	0.000000
RISK_SEA_PORT_CUST_PD(KUCHING, SGP)	0.000000	0.000000
RISK_SEA_PORT_CUST_PD(KUCHING, THAI)	0.000000	0.000000
RISK_SEA_PORT_CUST_PD(SIBU, JAPAN)	0.6531250E-03	0.000000
RISK_SEA_PORT_CUST_PD(SIBU, PEN_MSIA)	0.1514267E-03	0.000000
RISK_SEA_PORT_CUST_PD(SIBU, SGP)	0.2604167E-04	0.000000
RISK_SEA_PORT_CUST_PD(SIBU, THAI)	0.2116667E-04	0.000000
RISK_SEA_PORT_CUST_PD(MIRI, JAPAN)	0.000000	0.000000
RISK_SEA_PORT_CUST_PD(MIRI, PEN_MSIA)	0.000000	0.000000
RISK_SEA_PORT_CUST_PD(MIRI, SGP)	0.000000	0.000000
RISK_SEA_PORT_CUST_PD(MIRI, THAI)	0.000000	0.000000
FP_C_FUEL_SHIP_PORT_CUST(KUCHING, JAPA	0.000000	0.000000
FP_C_FUEL_SHIP_PORT_CUST(KUCHING, PEN_	257542.8	0.000000
FP_C_FUEL_SHIP_PORT_CUST(KUCHING, SGP)	0.000000	0.000000
FP_C_FUEL_SHIP_PORT_CUST(KUCHING, THAI	0.000000	0.000000
FP_C_FUEL_SHIP_PORT_CUST(SIBU, JAPAN)	725752.5	0.000000
FP_C_FUEL_SHIP_PORT_CUST(SIBU, PEN_MSI	168265.3	0.000000
FP_C_FUEL_SHIP_PORT_CUST(SIBU, SGP)	28937.50	0.000000
FP_C_FUEL_SHIP_PORT_CUST(SIBU, THAI)	23520.40	0.000000
FP_C_FUEL_SHIP_PORT_CUST(MIRI, JAPAN)	0.000000	0.000000
FP_C_FUEL_SHIP_PORT_CUST(MIRI, PEN_MSI	0.000000	0.000000
FP_C_FUEL_SHIP_PORT_CUST(MIRI, SGP)	0.000000	0.000000
FP_C_FUEL_SHIP_PORT_CUST(MIRI, THAI)	0.000000	0.000000
FP_H2O_FUEL_SHIP_PORT_CUST(KUCHING, JA	0.000000	0.000000
FP_H2O_FUEL_SHIP_PORT_CUST(KUCHING, PE	2588.563	0.000000
FP_H2O_FUEL_SHIP_PORT_CUST(KUCHING, SG	0.000000	0.000000
FP_H2O_FUEL_SHIP_PORT_CUST(KUCHING, TH	0.000000	0.000000
FP_H2O_FUEL_SHIP_PORT_CUST(SIBU, JAPAN	7294.538	0.000000
FP_H2O_FUEL_SHIP_PORT_CUST(SIBU, PEN_M	1691.235	0.000000
FP_H2O_FUEL_SHIP_PORT_CUST(SIBU, SGP)	290.8508	0.000000
FP_H2O_FUEL_SHIP_PORT_CUST(SIBU, THAI)	236.4035	0.000000
FP_H2O_FUEL_SHIP_PORT_CUST(MIRI, JAPAN	0.000000	0.000000
FP_H2O_FUEL_SHIP_PORT_CUST(MIRI, PEN_M	0.000000	0.000000

FP_H2O_FUEL_SHIP_PORT_CUST(MIRI, SGP)	0.000000	0.000000
FP_H2O_FUEL_SHIP_PORT_CUST(MIRI, THAI)	0.000000	0.000000
DEMAND_UP_CUSTOMER(STARCH, JAPAN)	13000.00	0.000000
DEMAND_UP_CUSTOMER(STARCH, PEN_MSIA)	30700.00	0.000000
DEMAND_UP_CUSTOMER(STARCH, SGP)	3000.000	0.000000
DEMAND_UP_CUSTOMER(STARCH, THAI)	1300.000	0.000000
DEMAND_LOW_CUSTOMER(STARCH, JAPAN)	12500.00	0.000000
DEMAND_LOW_CUSTOMER(STARCH, PEN_MSIA)	30000.00	0.000000
DEMAND_LOW_CUSTOMER(STARCH, SGP)	2500.000	0.000000
DEMAND_LOW_CUSTOMER(STARCH, THAI)	1000.000	0.000000
DISTANCE_PLANT_MILL(MUKAH, MUKAH_A)	76.00000	0.000000
DISTANCE_PLANT_MILL(MUKAH, MUKAH_B)	61.00000	0.000000
DISTANCE_PLANT_MILL(MUKAH, DALAT_A)	77.00000	0.000000
DISTANCE_PLANT_MILL(MUKAH, DALAT_B)	84.00000	0.000000
DISTANCE_PLANT_MILL(MUKAH, DALAT_C)	72.00000	0.000000
DISTANCE_PLANT_MILL(MUKAH, PUSA)	228.0000	0.000000
DISTANCE_PLANT_MILL(DALAT, MUKAH_A)	89.00000	0.000000
DISTANCE_PLANT_MILL(DALAT, MUKAH_B)	74.00000	0.000000
DISTANCE_PLANT_MILL(DALAT, DALAT_A)	63.00000	0.000000
DISTANCE_PLANT_MILL(DALAT, DALAT_B)	70.00000	0.000000
DISTANCE_PLANT_MILL(DALAT, DALAT_C)	58.00000	0.000000
DISTANCE_PLANT_MILL(DALAT, PUSA)	202.0000	0.000000
DISTANCE_PLANT_MILL(SARATOK, MUKAH_A)	251.0000	0.000000
DISTANCE_PLANT_MILL(SARATOK, MUKAH_B)	236.0000	0.000000
DISTANCE_PLANT_MILL(SARATOK, DALAT_A)	171.0000	0.000000
DISTANCE_PLANT_MILL(SARATOK, DALAT_B)	164.0000	0.000000
DISTANCE_PLANT_MILL(SARATOK, DALAT_C)	176.0000	0.000000
DISTANCE_PLANT_MILL(SARATOK, PUSA)	46.00000	0.000000
DISTANCE_PLANT_MILL(BETONG, MUKAH_A)	305.0000	0.000000
DISTANCE_PLANT_MILL(BETONG, MUKAH_B)	290.0000	0.000000
DISTANCE_PLANT_MILL(BETONG, DALAT_A)	220.0000	0.000000
DISTANCE_PLANT_MILL(BETONG, DALAT_B)	213.0000	0.000000
DISTANCE_PLANT_MILL(BETONG, DALAT_C)	225.0000	0.000000
DISTANCE_PLANT_MILL(BETONG, PUSA)	57.00000	0.000000
DISTANCE_MILL_PORT(MUKAH_A, KUCHING)	514.0000	0.000000
DISTANCE_MILL_PORT(MUKAH_A, SIBU)	138.0000	0.000000
DISTANCE_MILL_PORT(MUKAH_A, MIRI)	414.0000	0.000000
DISTANCE_MILL_PORT(MUKAH_B, KUCHING)	499.0000	0.000000
DISTANCE_MILL_PORT(MUKAH_B, SIBU)	123.0000	0.000000
DISTANCE_MILL_PORT(MUKAH_B, MIRI)	400.0000	0.000000
DISTANCE_MILL_PORT(DALAT_A, KUCHING)	429.0000	0.000000
DISTANCE_MILL_PORT(DALAT_A, SIBU)	53.00000	0.000000
DISTANCE_MILL_PORT(DALAT_A, MIRI)	358.0000	0.000000
DISTANCE_MILL_PORT(DALAT_B, KUCHING)	422.0000	0.000000
DISTANCE_MILL_PORT(DALAT_B, SIBU)	46.00000	0.000000
DISTANCE_MILL_PORT(DALAT_B, MIRI)	365.0000	0.000000
DISTANCE_MILL_PORT(DALAT_C, KUCHING)	434.0000	0.000000
DISTANCE_MILL_PORT(DALAT_C, SIBU)	58.00000	0.000000
DISTANCE_MILL_PORT(DALAT_C, MIRI)	353.0000	0.000000
DISTANCE_MILL_PORT(PUSA, KUCHING)	289.0000	0.000000
DISTANCE_MILL_PORT(PUSA, SIBU)	191.0000	0.000000
DISTANCE_MILL_PORT(PUSA, MIRI)	574.0000	0.000000
MAT_PLANT_RAW_MILL(MUKAH, LOG, MUKAH_A	1320000.	0.000000
MAT_PLANT_RAW_MILL(MUKAH, LOG, MUKAH_B	508000.0	0.000000
MAT_PLANT_RAW_MILL(MUKAH, LOG, DALAT_A	726000.0	0.000000
MAT_PLANT_RAW_MILL(MUKAH, LOG, DALAT_B	460000.0	0.000000
MAT_PLANT_RAW_MILL(MUKAH, LOG, DALAT_C	825000.0	0.000000
MAT_PLANT_RAW_MILL(MUKAH, LOG, PUSA)	0.000000	0.000000
MAT_PLANT_RAW_MILL(DALAT, LOG, MUKAH_A	0.000000	0.000000
MAT_PLANT_RAW_MILL(DALAT, LOG, MUKAH_B	0.000000	0.000000

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MAT_PLANT_RAW_MILL( DALAT, LOG, DALAT_A        0.000000            0.000000
MAT_PLANT_RAW_MILL( DALAT, LOG, DALAT_B        0.000000            0.000000
MAT_PLANT_RAW_MILL( DALAT, LOG, DALAT_C        0.000000            0.000000
  MAT_PLANT_RAW_MILL( DALAT, LOG, PUSA)        0.000000            0.000000
MAT_PLANT_RAW_MILL( SARATOK, LOG, MUKAH        0.000000            0.000000
MAT_PLANT_RAW_MILL( SARATOK, LOG, MUKAH        0.000000            0.000000
MAT_PLANT_RAW_MILL( SARATOK, LOG, DALAT        0.000000            0.000000
MAT_PLANT_RAW_MILL( SARATOK, LOG, DALAT        365000.0            0.000000
MAT_PLANT_RAW_MILL( SARATOK, LOG, DALAT        0.000000            0.000000
MAT_PLANT_RAW_MILL( SARATOK, LOG, PUSA)        396000.0            0.000000
MAT_PLANT_RAW_MILL( BETONG, LOG, MUKAH_        0.000000            0.000000
MAT_PLANT_RAW_MILL( BETONG, LOG, MUKAH_        0.000000            0.000000
MAT_PLANT_RAW_MILL( BETONG, LOG, DALAT_        0.000000            0.000000
MAT_PLANT_RAW_MILL( BETONG, LOG, DALAT_        0.000000            0.000000
MAT_PLANT_RAW_MILL( BETONG, LOG, DALAT_        0.000000            0.000000
 MAT_PLANT_RAW_MILL( BETONG, LOG, PUSA)        0.000000            0.000000
TRIP_PLANT_RAW_MILL( MUKAH, LOG, MUKAH_        6600.000          0.1430452E-04
TRIP_PLANT_RAW_MILL( MUKAH, LOG, MUKAH_        2540.000          0.1148126E-04
TRIP_PLANT_RAW_MILL( MUKAH, LOG, DALAT_        3630.000          0.1449274E-04
TRIP_PLANT_RAW_MILL( MUKAH, LOG, DALAT_        2300.000          0.1581026E-04
TRIP_PLANT_RAW_MILL( MUKAH, LOG, DALAT_        4125.000          0.1355165E-04
 TRIP_PLANT_RAW_MILL( MUKAH, LOG, PUSA)        0.000000          0.4291357E-04
TRIP_PLANT_RAW_MILL( DALAT, LOG, MUKAH_        0.000000          0.1675135E-04
TRIP_PLANT_RAW_MILL( DALAT, LOG, MUKAH_        0.000000          0.1392809E-04
TRIP_PLANT_RAW_MILL( DALAT, LOG, DALAT_        0.000000          0.1185770E-04
TRIP_PLANT_RAW_MILL( DALAT, LOG, DALAT_        0.000000          0.1317522E-04
TRIP_PLANT_RAW_MILL( DALAT, LOG, DALAT_        0.000000          0.1091661E-04
 TRIP_PLANT_RAW_MILL( DALAT, LOG, PUSA)        0.000000          0.3801992E-04
TRIP_PLANT_RAW_MILL( SARATOK, LOG, MUKA        0.000000          0.4724257E-04
TRIP_PLANT_RAW_MILL( SARATOK, LOG, MUKA        0.000000          0.4441931E-04
TRIP_PLANT_RAW_MILL( SARATOK, LOG, DALA        0.000000          0.3218518E-04
TRIP_PLANT_RAW_MILL( SARATOK, LOG, DALA        1825.000          0.3086766E-04
TRIP_PLANT_RAW_MILL( SARATOK, LOG, DALA        0.000000          0.3312627E-04
TRIP_PLANT_RAW_MILL( SARATOK, LOG, PUSA        1980.000          0.8658001E-05
TRIP_PLANT_RAW_MILL( BETONG, LOG, MUKAH        0.000000          0.5740631E-04
TRIP_PLANT_RAW_MILL( BETONG, LOG, MUKAH        0.000000          0.5458305E-04
TRIP_PLANT_RAW_MILL( BETONG, LOG, DALAT        0.000000          0.4140783E-04
TRIP_PLANT_RAW_MILL( BETONG, LOG, DALAT        0.000000          0.4009031E-04
TRIP_PLANT_RAW_MILL( BETONG, LOG, DALAT        0.000000          0.4234892E-04
TRIP_PLANT_RAW_MILL( BETONG, LOG, PUSA)        0.000000          0.1072839E-04
COST_TRAN_PLANT_MILL( MUKAH, LOG, MUKAH        2257200.            0.000000
COST_TRAN_PLANT_MILL( MUKAH, LOG, MUKAH        697230.0            0.000000
COST_TRAN_PLANT_MILL( MUKAH, LOG, DALAT        1257795.            0.000000
COST_TRAN_PLANT_MILL( MUKAH, LOG, DALAT        869400.0            0.000000
COST_TRAN_PLANT_MILL( MUKAH, LOG, DALAT        1336500.            0.000000
COST_TRAN_PLANT_MILL( MUKAH, LOG, PUSA)        0.000000            0.000000
COST_TRAN_PLANT_MILL( DALAT, LOG, MUKAH        0.000000            0.000000
COST_TRAN_PLANT_MILL( DALAT, LOG, MUKAH        0.000000            0.000000
COST_TRAN_PLANT_MILL( DALAT, LOG, DALAT        0.000000            0.000000
COST_TRAN_PLANT_MILL( DALAT, LOG, DALAT        0.000000            0.000000
COST_TRAN_PLANT_MILL( DALAT, LOG, DALAT        0.000000            0.000000
COST_TRAN_PLANT_MILL( DALAT, LOG, PUSA)        0.000000            0.000000
COST_TRAN_PLANT_MILL( SARATOK, LOG, MUK        0.000000            0.000000
COST_TRAN_PLANT_MILL( SARATOK, LOG, MUK        0.000000            0.000000
COST_TRAN_PLANT_MILL( SARATOK, LOG, DAL        0.000000            0.000000
COST_TRAN_PLANT_MILL( SARATOK, LOG, DAL        1346850.            0.000000
COST_TRAN_PLANT_MILL( SARATOK, LOG, DAL        0.000000            0.000000
COST_TRAN_PLANT_MILL( SARATOK, LOG, PUS        409860.0            0.000000
COST_TRAN_PLANT_MILL( BETONG, LOG, MUKA        0.000000            0.000000
COST_TRAN_PLANT_MILL( BETONG, LOG, MUKA        0.000000            0.000000
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COST_TRAN_PLANT_MILL(BETONG, LOG, DALA	0.000000	0.000000
COST_TRAN_PLANT_MILL(BETONG, LOG, DALA	0.000000	0.000000
COST_TRAN_PLANT_MILL(BETONG, LOG, DALA	0.000000	0.000000
COST_TRAN_PLANT_MILL(BETONG, LOG, PUSA	0.000000	0.000000
SELL_COST_PLANT_RAW_MILL(MUKAH, LOG, M	10.00000	0.000000
SELL_COST_PLANT_RAW_MILL(MUKAH, LOG, M	10.00000	0.000000
SELL_COST_PLANT_RAW_MILL(MUKAH, LOG, D	10.00000	0.000000
SELL_COST_PLANT_RAW_MILL(MUKAH, LOG, D	10.00000	0.000000
SELL_COST_PLANT_RAW_MILL(MUKAH, LOG, D	10.00000	0.000000
SELL_COST_PLANT_RAW_MILL(MUKAH, LOG, P	10.00000	0.000000
SELL_COST_PLANT_RAW_MILL(DALAT, LOG, M	12.00000	0.000000
SELL_COST_PLANT_RAW_MILL(DALAT, LOG, M	12.00000	0.000000
SELL_COST_PLANT_RAW_MILL(DALAT, LOG, D	12.00000	0.000000
SELL_COST_PLANT_RAW_MILL(DALAT, LOG, D	12.00000	0.000000
SELL_COST_PLANT_RAW_MILL(DALAT, LOG, D	12.00000	0.000000
SELL_COST_PLANT_RAW_MILL(DALAT, LOG, P	12.00000	0.000000
SELL_COST_PLANT_RAW_MILL(SARATOK, LOG,	8.000000	0.000000
SELL_COST_PLANT_RAW_MILL(SARATOK, LOG,	8.000000	0.000000
SELL_COST_PLANT_RAW_MILL(SARATOK, LOG,	8.000000	0.000000
SELL_COST_PLANT_RAW_MILL(SARATOK, LOG,	8.000000	0.000000
SELL_COST_PLANT_RAW_MILL(SARATOK, LOG,	8.000000	0.000000
SELL_COST_PLANT_RAW_MILL(SARATOK, LOG,	8.000000	0.000000
SELL_COST_PLANT_RAW_MILL(BETONG, LOG,	9.000000	0.000000
SELL_COST_PLANT_RAW_MILL(BETONG, LOG,	9.000000	0.000000
SELL_COST_PLANT_RAW_MILL(BETONG, LOG,	9.000000	0.000000
SELL_COST_PLANT_RAW_MILL(BETONG, LOG,	9.000000	0.000000
SELL_COST_PLANT_RAW_MILL(BETONG, LOG,	9.000000	0.000000
SELL_COST_PLANT_RAW_MILL(BETONG, LOG,	9.000000	0.000000
RISK_TRAN_PL_ML_D(MUKAH, LOG, MUKAH_A)	139.4448	0.000000
RISK_TRAN_PL_ML_D(MUKAH, LOG, MUKAH_B)	43.07332	0.000000
RISK_TRAN_PL_ML_D(MUKAH, LOG, DALAT_A)	20.48554	0.000000
RISK_TRAN_PL_ML_D(MUKAH, LOG, DALAT_B)	13.42740	0.000000
RISK_TRAN_PL_ML_D(MUKAH, LOG, DALAT_C)	22.70565	0.000000
RISK_TRAN_PL_ML_D(MUKAH, LOG, PUSA)	0.000000	0.000000
RISK_TRAN_PL_ML_D(DALAT, LOG, MUKAH_A)	0.000000	0.000000
RISK_TRAN_PL_ML_D(DALAT, LOG, MUKAH_B)	0.000000	0.000000
RISK_TRAN_PL_ML_D(DALAT, LOG, DALAT_A)	0.000000	0.000000
RISK_TRAN_PL_ML_D(DALAT, LOG, DALAT_B)	0.000000	0.000000
RISK_TRAN_PL_ML_D(DALAT, LOG, DALAT_C)	0.000000	0.000000
RISK_TRAN_PL_ML_D(DALAT, LOG, PUSA)	0.000000	0.000000
RISK_TRAN_PL_ML_D(SARATOK, LOG, MUKAH_	0.000000	0.000000
RISK_TRAN_PL_ML_D(SARATOK, LOG, MUKAH_	0.000000	0.000000
RISK_TRAN_PL_ML_D(SARATOK, LOG, DALAT_	0.000000	0.000000
RISK_TRAN_PL_ML_D(SARATOK, LOG, DALAT_	171.9599	0.000000
RISK_TRAN_PL_ML_D(SARATOK, LOG, DALAT_	0.000000	0.000000
RISK_TRAN_PL_ML_D(SARATOK, LOG, PUSA)	19.38618	0.000000
RISK_TRAN_PL_ML_D(BETONG, LOG, MUKAH_A	0.000000	0.000000
RISK_TRAN_PL_ML_D(BETONG, LOG, MUKAH_B	0.000000	0.000000
RISK_TRAN_PL_ML_D(BETONG, LOG, DALAT_A	0.000000	0.000000
RISK_TRAN_PL_ML_D(BETONG, LOG, DALAT_B	0.000000	0.000000
RISK_TRAN_PL_ML_D(BETONG, LOG, DALAT_C	0.000000	0.000000
RISK_TRAN_PL_ML_D(BETONG, LOG, PUSA)	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(MUKAH, LOG, MUKAH_	41.83344	0.000000
RISK_TRAN_PL_ML_NPD(MUKAH, LOG, MUKAH_	12.92200	0.000000
RISK_TRAN_PL_ML_NPD(MUKAH, LOG, DALAT_	36.02630	0.000000
RISK_TRAN_PL_ML_NPD(MUKAH, LOG, DALAT_	25.06448	0.000000
RISK_TRAN_PL_ML_NPD(MUKAH, LOG, DALAT_	38.07210	0.000000
RISK_TRAN_PL_ML_NPD(MUKAH, LOG, PUSA)	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(DALAT, LOG, MUKAH_	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(DALAT, LOG, MUKAH_	0.000000	0.000000

RISK_TRAN_PL_ML_NPD(DALAT, LOG, DALAT_	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(DALAT, LOG, DALAT_	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(DALAT, LOG, DALAT_	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(DALAT, LOG, PUSA)	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(SARATOK, LOG, MUKA	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(SARATOK, LOG, MUKA	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(SARATOK, LOG, DALA	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(SARATOK, LOG, DALA	106.2562	0.000000
RISK_TRAN_PL_ML_NPD(SARATOK, LOG, DALA	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(SARATOK, LOG, PUSA	4.623696	0.000000
RISK_TRAN_PL_ML_NPD(BETONG, LOG, MUKAH	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(BETONG, LOG, MUKAH	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(BETONG, LOG, DALAT	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(BETONG, LOG, DALAT	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(BETONG, LOG, DALAT	0.000000	0.000000
RISK_TRAN_PL_ML_NPD(BETONG, LOG, PUSA)	0.000000	0.000000
RISK_TRAN_PL_ML_PD(MUKAH, LOG, MUKAH_A	111.3552	0.000000
RISK_TRAN_PL_ML_PD(MUKAH, LOG, MUKAH_B	34.39668	0.000000
RISK_TRAN_PL_ML_PD(MUKAH, LOG, DALAT_A	17.63962	0.000000
RISK_TRAN_PL_ML_PD(MUKAH, LOG, DALAT_B	11.62420	0.000000
RISK_TRAN_PL_ML_PD(MUKAH, LOG, DALAT_C	19.47165	0.000000
RISK_TRAN_PL_ML_PD(MUKAH, LOG, PUSA)	0.000000	0.000000
RISK_TRAN_PL_ML_PD(DALAT, LOG, MUKAH_A	0.000000	0.000000
RISK_TRAN_PL_ML_PD(DALAT, LOG, MUKAH_B	0.000000	0.000000
RISK_TRAN_PL_ML_PD(DALAT, LOG, DALAT_A	0.000000	0.000000
RISK_TRAN_PL_ML_PD(DALAT, LOG, DALAT_B	0.000000	0.000000
RISK_TRAN_PL_ML_PD(DALAT, LOG, DALAT_C	0.000000	0.000000
RISK_TRAN_PL_ML_PD(DALAT, LOG, PUSA)	0.000000	0.000000
RISK_TRAN_PL_ML_PD(SARATOK, LOG, MUKAH	0.000000	0.000000
RISK_TRAN_PL_ML_PD(SARATOK, LOG, MUKAH	0.000000	0.000000
RISK_TRAN_PL_ML_PD(SARATOK, LOG, DALAT	0.000000	0.000000
RISK_TRAN_PL_ML_PD(SARATOK, LOG, DALAT	141.5317	0.000000
RISK_TRAN_PL_ML_PD(SARATOK, LOG, DALAT	0.000000	0.000000
RISK_TRAN_PL_ML_PD(SARATOK, LOG, PUSA)	39.57228	0.000000
RISK_TRAN_PL_ML_PD(BETONG, LOG, MUKAH_	0.000000	0.000000
RISK_TRAN_PL_ML_PD(BETONG, LOG, MUKAH_	0.000000	0.000000
RISK_TRAN_PL_ML_PD(BETONG, LOG, DALAT_	0.000000	0.000000
RISK_TRAN_PL_ML_PD(BETONG, LOG, DALAT_	0.000000	0.000000
RISK_TRAN_PL_ML_PD(BETONG, LOG, DALAT_	0.000000	0.000000
RISK_TRAN_PL_ML_PD(BETONG, LOG, PUSA)	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(MUKAH, LOG,	461472.0	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(MUKAH, LOG,	142544.8	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(MUKAH, LOG,	257149.2	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(MUKAH, LOG,	177744.0	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(MUKAH, LOG,	273240.0	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(MUKAH, LOG,	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(DALAT, LOG,	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(DALAT, LOG,	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(DALAT, LOG,	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(DALAT, LOG,	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(DALAT, LOG,	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(DALAT, LOG,	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(SARATOK, LO	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(SARATOK, LO	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(SARATOK, LO	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(SARATOK, LO	275356.0	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(SARATOK, LO	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(SARATOK, LO	83793.60	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(BETONG, LOG	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(BETONG, LOG	0.000000	0.000000

FP_C_FUEL_LORRY_PLANT_MILL(BETONG, LOG	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(BETONG, LOG	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(BETONG, LOG	0.000000	0.000000
FP_C_FUEL_LORRY_PLANT_MILL(BETONG, LOG	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(MUKAH, LO	122059.3	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(MUKAH, LO	37703.10	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(MUKAH, LO	68015.96	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(MUKAH, LO	47013.29	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(MUKAH, LO	72271.98	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(MUKAH, LO	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(DALAT, LO	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(DALAT, LO	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(DALAT, LO	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(DALAT, LO	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(DALAT, LO	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(DALAT, LO	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(SARATOK,	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(SARATOK,	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(SARATOK,	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(SARATOK,	72831.66	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(SARATOK,	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(SARATOK,	22163.41	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(BETONG, L	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(BETONG, L	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(BETONG, L	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(BETONG, L	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(BETONG, L	0.000000	0.000000
FP_H2O_FUEL_LORRY_PLANT_MILL(BETONG, L	0.000000	0.000000
MAT_RAW_MILL_PROD(LOG, MUKAH_A, STARCH	0.1320000E+08	0.000000
MAT_RAW_MILL_PROD(LOG, MUKAH_B, STARCH	5080000.	0.000000
MAT_RAW_MILL_PROD(LOG, DALAT_A, STARCH	7260000.	0.000000
MAT_RAW_MILL_PROD(LOG, DALAT_B, STARCH	8250000.	0.000000
MAT_RAW_MILL_PROD(LOG, DALAT_C, STARCH	8250000.	0.000000
MAT_RAW_MILL_PROD(LOG, PUSA, STARCH)	3960000.	0.000000
CONV_RAW_MILL_PROD(LOG, MUKAH_A, STARC	0.2000000	0.000000
CONV_RAW_MILL_PROD(LOG, MUKAH_B, STARC	0.2000000	0.000000
CONV_RAW_MILL_PROD(LOG, DALAT_A, STARC	0.2000000	0.000000
CONV_RAW_MILL_PROD(LOG, DALAT_B, STARC	0.2000000	0.000000
CONV_RAW_MILL_PROD(LOG, DALAT_C, STARC	0.2000000	0.000000
CONV_RAW_MILL_PROD(LOG, PUSA, STARCH)	0.2000000	0.000000
CAPACITY_RAW_MILL_PROD(LOG, MUKAH_A, S	13200.00	0.000000
CAPACITY_RAW_MILL_PROD(LOG, MUKAH_B, S	8250.000	0.000000
CAPACITY_RAW_MILL_PROD(LOG, DALAT_A, S	7260.000	0.000000
CAPACITY_RAW_MILL_PROD(LOG, DALAT_B, S	8250.000	0.000000
CAPACITY_RAW_MILL_PROD(LOG, DALAT_C, S	8250.000	0.000000
CAPACITY_RAW_MILL_PROD(LOG, PUSA, STAR	3960.000	0.000000
COST_PROCESS_MILL(LOG, MUKAH_A, STARCH	1425600.	0.000000
COST_PROCESS_MILL(LOG, MUKAH_B, STARCH	584200.0	0.000000
COST_PROCESS_MILL(LOG, DALAT_A, STARCH	849420.0	0.000000
COST_PROCESS_MILL(LOG, DALAT_B, STARCH	924000.0	0.000000
COST_PROCESS_MILL(LOG, DALAT_C, STARCH	1006500.	0.000000
COST_PROCESS_MILL(LOG, PUSA, STARCH)	3762000.	0.000000
UNITCOST_PROCESS_MILL(LOG, MUKAH_A, ST	0.1080000	0.000000
UNITCOST_PROCESS_MILL(LOG, MUKAH_B, ST	0.1150000	0.000000
UNITCOST_PROCESS_MILL(LOG, DALAT_A, ST	0.1170000	0.000000
UNITCOST_PROCESS_MILL(LOG, DALAT_B, ST	0.1120000	0.000000
UNITCOST_PROCESS_MILL(LOG, DALAT_C, ST	0.1220000	0.000000
UNITCOST_PROCESS_MILL(LOG, PUSA, STARC	0.9500000	0.000000
UFP_C_POWER_RAW_MILL_PROD(LOG, MUKAH_A	0.8990000	0.000000
UFP_C_POWER_RAW_MILL_PROD(LOG, MUKAH_B	0.8990000	0.000000

UFP_C_POWER_RAW_MILL_PROD(LOG, DALAT_A	0.8990000	0.000000
UFP_C_POWER_RAW_MILL_PROD(LOG, DALAT_B	0.8990000	0.000000
UFP_C_POWER_RAW_MILL_PROD(LOG, DALAT_C	0.8990000	0.000000
UFP_C_POWER_RAW_MILL_PROD(LOG, PUSA, S	0.8990000	0.000000
ENERGY_REQ_RAW_MILL_PROD(LOG, MUKAH_A,	0.2200000	0.000000
ENERGY_REQ_RAW_MILL_PROD(LOG, MUKAH_B,	0.2300000	0.000000
ENERGY_REQ_RAW_MILL_PROD(LOG, DALAT_A,	0.2350000	0.000000
ENERGY_REQ_RAW_MILL_PROD(LOG, DALAT_B,	0.2250000	0.000000
ENERGY_REQ_RAW_MILL_PROD(LOG, DALAT_C,	0.2400000	0.000000
ENERGY_REQ_RAW_MILL_PROD(LOG, PUSA, ST	0.2180000	0.000000
FP_C_POWER_RAW_MILL_PROD(LOG, MUKAH_A,	2610696.	0.000000
FP_C_POWER_RAW_MILL_PROD(LOG, MUKAH_B,	1050392.	0.000000
FP_C_POWER_RAW_MILL_PROD(LOG, DALAT_A,	1533784.	0.000000
FP_C_POWER_RAW_MILL_PROD(LOG, DALAT_B,	1668769.	0.000000
FP_C_POWER_RAW_MILL_PROD(LOG, DALAT_C,	1780020.	0.000000
FP_C_POWER_RAW_MILL_PROD(LOG, PUSA, ST	776088.7	0.000000
UFP_H2O_BW(LOG, MUKAH_A, STARCH)	3.500000	0.000000
UFP_H2O_BW(LOG, MUKAH_B, STARCH)	5.000000	0.000000
UFP_H2O_BW(LOG, DALAT_A, STARCH)	3.200000	0.000000
UFP_H2O_BW(LOG, DALAT_B, STARCH)	3.500000	0.000000
UFP_H2O_BW(LOG, DALAT_C, STARCH)	4.000000	0.000000
UFP_H2O_BW(LOG, PUSA, STARCH)	4.400000	0.000000
H2O_REQ_RAW_MILL_PROD(LOG, MUKAH_A, ST	30.00000	0.000000
H2O_REQ_RAW_MILL_PROD(LOG, MUKAH_B, ST	35.00000	0.000000
H2O_REQ_RAW_MILL_PROD(LOG, DALAT_A, ST	32.00000	0.000000
H2O_REQ_RAW_MILL_PROD(LOG, DALAT_B, ST	30.50000	0.000000
H2O_REQ_RAW_MILL_PROD(LOG, DALAT_C, ST	33.00000	0.000000
H2O_REQ_RAW_MILL_PROD(LOG, PUSA, STARC	28.50000	0.000000
WW_OUT_RAW_MILL_PROD(LOG, MUKAH_A, STA	26.50000	0.000000
WW_OUT_RAW_MILL_PROD(LOG, MUKAH_B, STA	30.00000	0.000000
WW_OUT_RAW_MILL_PROD(LOG, DALAT_A, STA	28.80000	0.000000
WW_OUT_RAW_MILL_PROD(LOG, DALAT_B, STA	27.00000	0.000000
WW_OUT_RAW_MILL_PROD(LOG, DALAT_C, STA	29.00000	0.000000
WW_OUT_RAW_MILL_PROD(LOG, PUSA, STARCH	24.10000	0.000000
FP_H2O_BW(LOG, MUKAH_A, STARCH)	46200.00	0.000000
FP_H2O_BW(LOG, MUKAH_B, STARCH)	25400.00	0.000000
FP_H2O_BW(LOG, DALAT_A, STARCH)	23232.00	0.000000
FP_H2O_BW(LOG, DALAT_B, STARCH)	28875.00	0.000000
FP_H2O_BW(LOG, DALAT_C, STARCH)	33000.00	0.000000
FP_H2O_BW(LOG, PUSA, STARCH)	17424.00	0.000000
MAX_GW(LOG, MUKAH_A, STARCH)	1537.000	0.000000
MAX_GW(LOG, MUKAH_B, STARCH)	2400.000	0.000000
MAX_GW(LOG, DALAT_A, STARCH)	1900.800	0.000000
MAX_GW(LOG, DALAT_B, STARCH)	1620.000	0.000000
MAX_GW(LOG, DALAT_C, STARCH)	2030.000	0.000000
MAX_GW(LOG, PUSA, STARCH)	1277.300	0.000000
FP_H20_GW(LOG, MUKAH_A, STARCH)	0.2028840E+08	0.000000
FP_H20_GW(LOG, MUKAH_B, STARCH)	0.1219200E+08	0.000000
FP_H20_GW(LOG, DALAT_A, STARCH)	0.1379981E+08	0.000000
FP_H20_GW(LOG, DALAT_B, STARCH)	0.1336500E+08	0.000000
FP_H20_GW(LOG, DALAT_C, STARCH)	0.1674750E+08	0.000000
FP_H20_GW(LOG, PUSA, STARCH)	5058108.	0.000000
UFP_H2O_POWER(LOG, MUKAH_A, STARCH)	0.2185500E-02	0.000000
UFP_H2O_POWER(LOG, MUKAH_B, STARCH)	0.2185500E-02	0.000000
UFP_H2O_POWER(LOG, DALAT_A, STARCH)	0.2185500E-02	0.000000
UFP_H2O_POWER(LOG, DALAT_B, STARCH)	0.2185500E-02	0.000000
UFP_H2O_POWER(LOG, DALAT_C, STARCH)	0.2185500E-02	0.000000
UFP_H2O_POWER(LOG, PUSA, STARCH)	0.2185500E-02	0.000000
FP_H2O_POWER(LOG, MUKAH_A, STARCH)	6346.692	0.000000
FP_H2O_POWER(LOG, MUKAH_B, STARCH)	2553.538	0.000000

FP_H2O_POWER(LOG, DALAT_A, STARCH)	3728.682	0.000000
FP_H2O_POWER(LOG, DALAT_B, STARCH)	4056.834	0.000000
FP_H2O_POWER(LOG, DALAT_C, STARCH)	4327.290	0.000000
FP_H2O_POWER(LOG, PUSA, STARCH)	1886.698	0.000000
MAT_MILL_PROD_PORT(MUKAH_A, STARCH, KU	6710000.	0.000000
MAT_MILL_PROD_PORT(MUKAH_A, STARCH, SI	6490000.	0.000000
MAT_MILL_PROD_PORT(MUKAH_A, STARCH, MI	0.000000	0.4893653E-08
MAT_MILL_PROD_PORT(MUKAH_B, STARCH, KU	0.000000	0.000000
MAT_MILL_PROD_PORT(MUKAH_B, STARCH, SI	5080000.	0.000000
MAT_MILL_PROD_PORT(MUKAH_B, STARCH, MI	0.000000	0.4810001E-08
MAT_MILL_PROD_PORT(DALAT_A, STARCH, KU	0.000000	0.000000
MAT_MILL_PROD_PORT(DALAT_A, STARCH, SI	7260000.	0.000000
MAT_MILL_PROD_PORT(DALAT_A, STARCH, MI	0.000000	0.4893653E-08
MAT_MILL_PROD_PORT(DALAT_B, STARCH, KU	0.000000	0.000000
MAT_MILL_PROD_PORT(DALAT_B, STARCH, SI	8250000.	0.000000
MAT_MILL_PROD_PORT(DALAT_B, STARCH, MI	0.000000	0.4684523E-08
MAT_MILL_PROD_PORT(DALAT_C, STARCH, KU	8250000.	0.000000
MAT_MILL_PROD_PORT(DALAT_C, STARCH, SI	0.000000	0.000000
MAT_MILL_PROD_PORT(DALAT_C, STARCH, MI	0.000000	0.5102783E-08
MAT_MILL_PROD_PORT(PUSA, STARCH, KUCHI	3960000.	0.000000
MAT_MILL_PROD_PORT(PUSA, STARCH, SIBU)	0.000000	0.3484114E-07
MAT_MILL_PROD_PORT(PUSA, STARCH, MIRI)	0.000000	0.3973479E-07
TRIP_MILL_PROD_PORT(MUKAH_A, STARCH, K	671.0000	-0.2516676E-03
TRIP_MILL_PROD_PORT(MUKAH_A, STARCH, S	649.0000	0.2597400E-04
TRIP_MILL_PROD_PORT(MUKAH_A, STARCH, M	0.000000	0.7792201E-04
TRIP_MILL_PROD_PORT(MUKAH_B, STARCH, K	0.000000	-0.2553274E-03
TRIP_MILL_PROD_PORT(MUKAH_B, STARCH, S	508.0000	0.2231422E-04
TRIP_MILL_PROD_PORT(MUKAH_B, STARCH, M	0.000000	0.7528697E-04
TRIP_MILL_PROD_PORT(DALAT_A, STARCH, K	0.000000	-0.2676661E-03
TRIP_MILL_PROD_PORT(DALAT_A, STARCH, S	726.0000	0.9975523E-05
TRIP_MILL_PROD_PORT(DALAT_A, STARCH, M	0.000000	0.6738184E-04
TRIP_MILL_PROD_PORT(DALAT_B, STARCH, K	0.000000	-0.2710749E-03
TRIP_MILL_PROD_PORT(DALAT_B, STARCH, S	825.0000	0.6566697E-05
TRIP_MILL_PROD_PORT(DALAT_B, STARCH, M	0.000000	0.6869936E-04
TRIP_MILL_PROD_PORT(DALAT_C, STARCH, K	825.0000	-0.2646337E-03
TRIP_MILL_PROD_PORT(DALAT_C, STARCH, S	0.000000	0.1091661E-04
TRIP_MILL_PROD_PORT(DALAT_C, STARCH, M	0.000000	0.6644075E-04
TRIP_MILL_PROD_PORT(PUSA, STARCH, KUCH	396.0000	0.5439483E-04
TRIP_MILL_PROD_PORT(PUSA, STARCH, SIBU	0.000000	0.3594953E-04
TRIP_MILL_PROD_PORT(PUSA, STARCH, MIRI	0.000000	0.1080368E-03
COST_TRAN_MILL_PORT(MUKAH_A, STARCH, K	1552023.	0.000000
COST_TRAN_MILL_PORT(MUKAH_A, STARCH, S	403029.0	0.000000
COST_TRAN_MILL_PORT(MUKAH_A, STARCH, M	0.000000	0.000000
COST_TRAN_MILL_PORT(MUKAH_B, STARCH, K	0.000000	0.000000
COST_TRAN_MILL_PORT(MUKAH_B, STARCH, S	281178.0	0.000000
COST_TRAN_MILL_PORT(MUKAH_B, STARCH, M	0.000000	0.000000
COST_TRAN_MILL_PORT(DALAT_A, STARCH, K	0.000000	0.000000
COST_TRAN_MILL_PORT(DALAT_A, STARCH, S	173151.0	0.000000
COST_TRAN_MILL_PORT(DALAT_A, STARCH, M	0.000000	0.000000
COST_TRAN_MILL_PORT(DALAT_B, STARCH, K	0.000000	0.000000
COST_TRAN_MILL_PORT(DALAT_B, STARCH, S	170775.0	0.000000
COST_TRAN_MILL_PORT(DALAT_B, STARCH, M	0.000000	0.000000
COST_TRAN_MILL_PORT(DALAT_C, STARCH, K	1611225.	0.000000
COST_TRAN_MILL_PORT(DALAT_C, STARCH, S	0.000000	0.000000
COST_TRAN_MILL_PORT(DALAT_C, STARCH, M	0.000000	0.000000
COST_TRAN_MILL_PORT(PUSA, STARCH, KUCH	514998.0	0.000000
COST_TRAN_MILL_PORT(PUSA, STARCH, SIBU	0.000000	0.000000
COST_TRAN_MILL_PORT(PUSA, STARCH, MIRI	0.000000	0.000000
SELL_COST_MILL_PORT(MUKAH_A, STARCH, K	1.600000	0.000000
SELL_COST_MILL_PORT(MUKAH_A, STARCH, S	1.500000	0.000000

SELL_COST_MILL_PORT(MUKAH_A, STARCH, M	1.550000	0.000000
SELL_COST_MILL_PORT(MUKAH_B, STARCH, K	1.600000	0.000000
SELL_COST_MILL_PORT(MUKAH_B, STARCH, S	1.500000	0.000000
SELL_COST_MILL_PORT(MUKAH_B, STARCH, M	1.550000	0.000000
SELL_COST_MILL_PORT(DALAT_A, STARCH, K	1.600000	0.000000
SELL_COST_MILL_PORT(DALAT_A, STARCH, S	1.500000	0.000000
SELL_COST_MILL_PORT(DALAT_A, STARCH, M	1.550000	0.000000
SELL_COST_MILL_PORT(DALAT_B, STARCH, K	1.600000	0.000000
SELL_COST_MILL_PORT(DALAT_B, STARCH, S	1.500000	0.000000
SELL_COST_MILL_PORT(DALAT_B, STARCH, M	1.550000	0.000000
SELL_COST_MILL_PORT(DALAT_C, STARCH, K	1.600000	0.000000
SELL_COST_MILL_PORT(DALAT_C, STARCH, S	1.500000	0.000000
SELL_COST_MILL_PORT(DALAT_C, STARCH, M	1.550000	0.000000
SELL_COST_MILL_PORT(PUSA, STARCH, KUCH	1.600000	0.000000
SELL_COST_MILL_PORT(PUSA, STARCH, SIBU	1.500000	0.000000
SELL_COST_MILL_PORT(PUSA, STARCH, MIRI	1.550000	0.000000
RISK_TRAN_ML_PORT_D(MUKAH_A, STARCH, K	182.5730	0.000000
RISK_TRAN_ML_PORT_D(MUKAH_A, STARCH, S	42.98158	0.000000
RISK_TRAN_ML_PORT_D(MUKAH_A, STARCH, M	0.000000	0.000000
RISK_TRAN_ML_PORT_D(MUKAH_B, STARCH, K	0.000000	0.000000
RISK_TRAN_ML_PORT_D(MUKAH_B, STARCH, S	31.52516	0.000000
RISK_TRAN_ML_PORT_D(MUKAH_B, STARCH, M	0.000000	0.000000
RISK_TRAN_ML_PORT_D(DALAT_A, STARCH, K	0.000000	0.000000
RISK_TRAN_ML_PORT_D(DALAT_A, STARCH, S	32.56052	0.000000
RISK_TRAN_ML_PORT_D(DALAT_A, STARCH, M	0.000000	0.000000
RISK_TRAN_ML_PORT_D(DALAT_B, STARCH, K	0.000000	0.000000
RISK_TRAN_ML_PORT_D(DALAT_B, STARCH, S	36.84005	0.000000
RISK_TRAN_ML_PORT_D(DALAT_B, STARCH, M	0.000000	0.000000
RISK_TRAN_ML_PORT_D(DALAT_C, STARCH, K	206.9527	0.000000
RISK_TRAN_ML_PORT_D(DALAT_C, STARCH, S	0.000000	0.000000
RISK_TRAN_ML_PORT_D(DALAT_C, STARCH, M	0.000000	0.000000
RISK_TRAN_ML_PORT_D(PUSA, STARCH, KUCH	65.99732	0.000000
RISK_TRAN_ML_PORT_D(PUSA, STARCH, SIBU	0.000000	0.000000
RISK_TRAN_ML_PORT_D(PUSA, STARCH, MIRI	0.000000	0.000000
RISK_TRAN_ML_PORT_NPD(MUKAH_A, STARCH,	142.7541	0.000000
RISK_TRAN_ML_PORT_NPD(MUKAH_A, STARCH,	6.188475	0.000000
RISK_TRAN_ML_PORT_NPD(MUKAH_A, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_NPD(MUKAH_B, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_NPD(MUKAH_B, STARCH,	4.208475	0.000000
RISK_TRAN_ML_PORT_NPD(MUKAH_B, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_NPD(DALAT_A, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_NPD(DALAT_A, STARCH,	1.412796	0.000000
RISK_TRAN_ML_PORT_NPD(DALAT_A, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_NPD(DALAT_B, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_NPD(DALAT_B, STARCH,	0.8027250	0.000000
RISK_TRAN_ML_PORT_NPD(DALAT_B, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_NPD(DALAT_C, STARCH,	169.8295	0.000000
RISK_TRAN_ML_PORT_NPD(DALAT_C, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_NPD(DALAT_C, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_NPD(PUSA, STARCH, KU	59.16546	0.000000
RISK_TRAN_ML_PORT_NPD(PUSA, STARCH, SI	0.000000	0.000000
RISK_TRAN_ML_PORT_NPD(PUSA, STARCH, MI	0.000000	0.000000
RISK_TRAN_ML_PORT_PD(MUKAH_A, STARCH,	155.6515	0.000000
RISK_TRAN_ML_PORT_PD(MUKAH_A, STARCH,	12.06854	0.000000
RISK_TRAN_ML_PORT_PD(MUKAH_A, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_PD(MUKAH_B, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_PD(MUKAH_B, STARCH,	7.754925	0.000000
RISK_TRAN_ML_PORT_PD(MUKAH_B, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_PD(DALAT_A, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_PD(DALAT_A, STARCH,	1.069688	0.000000

RISK_TRAN_ML_PORT_PD(DALAT_A, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_PD(DALAT_B, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_PD(DALAT_B, STARCH,	1.055010	0.000000
RISK_TRAN_ML_PORT_PD(DALAT_B, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_PD(DALAT_C, STARCH,	177.3637	0.000000
RISK_TRAN_ML_PORT_PD(DALAT_C, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_PD(DALAT_C, STARCH,	0.000000	0.000000
RISK_TRAN_ML_PORT_PD(PUSA, STARCH, KUC	54.89340	0.000000
RISK_TRAN_ML_PORT_PD(PUSA, STARCH, SIB	0.000000	0.000000
RISK_TRAN_ML_PORT_PD(PUSA, STARCH, MIR	0.000000	0.000000
FP_C_FUEL_LORRY_MILL_PORT(MUKAH_A, STA	317302.5	0.000000
FP_C_FUEL_LORRY_MILL_PORT(MUKAH_A, STA	82397.04	0.000000
FP_C_FUEL_LORRY_MILL_PORT(MUKAH_A, STA	0.000000	0.000000
FP_C_FUEL_LORRY_MILL_PORT(MUKAH_B, STA	0.000000	0.000000
FP_C_FUEL_LORRY_MILL_PORT(MUKAH_B, STA	57485.28	0.000000
FP_C_FUEL_LORRY_MILL_PORT(MUKAH_B, STA	0.000000	0.000000
FP_C_FUEL_LORRY_MILL_PORT(DALAT_A, STA	0.000000	0.000000
FP_C_FUEL_LORRY_MILL_PORT(DALAT_A, STA	35399.76	0.000000
FP_C_FUEL_LORRY_MILL_PORT(DALAT_A, STA	0.000000	0.000000
FP_C_FUEL_LORRY_MILL_PORT(DALAT_B, STA	0.000000	0.000000
FP_C_FUEL_LORRY_MILL_PORT(DALAT_B, STA	34914.00	0.000000
FP_C_FUEL_LORRY_MILL_PORT(DALAT_B, STA	0.000000	0.000000
FP_C_FUEL_LORRY_MILL_PORT(DALAT_C, STA	329406.0	0.000000
FP_C_FUEL_LORRY_MILL_PORT(DALAT_C, STA	0.000000	0.000000
FP_C_FUEL_LORRY_MILL_PORT(DALAT_C, STA	0.000000	0.000000
FP_C_FUEL_LORRY_MILL_PORT(PUSA, STARCH	105288.5	0.000000
FP_C_FUEL_LORRY_MILL_PORT(PUSA, STARCH	0.000000	0.000000
FP_C_FUEL_LORRY_MILL_PORT(PUSA, STARCH	0.000000	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(MUKAH_A, S	83926.51	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(MUKAH_A, S	21794.02	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(MUKAH_A, S	0.000000	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(MUKAH_B, S	0.000000	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(MUKAH_B, S	15204.86	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(MUKAH_B, S	0.000000	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(DALAT_A, S	0.000000	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(DALAT_A, S	9363.237	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(DALAT_A, S	0.000000	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(DALAT_B, S	0.000000	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(DALAT_B, S	9234.753	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(DALAT_B, S	0.000000	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(DALAT_C, S	87127.89	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(DALAT_C, S	0.000000	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(DALAT_C, S	0.000000	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(PUSA, STAR	27848.80	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(PUSA, STAR	0.000000	0.000000
FP_H2O_FUEL_LORRY_MILL_PORT(PUSA, STAR	0.000000	0.000000
MAT_PROD_PORT_CUST(STARCH, KUCHING, JA	0.000000	0.000000
MAT_PROD_PORT_CUST(STARCH, KUCHING, PE	0.1892000E+08	0.000000
MAT_PROD_PORT_CUST(STARCH, KUCHING, SG	0.000000	0.000000
MAT_PROD_PORT_CUST(STARCH, KUCHING, TH	0.000000	0.000000
MAT_PROD_PORT_CUST(STARCH, SIBU, JAPAN	0.1250000E+08	0.000000
MAT_PROD_PORT_CUST(STARCH, SIBU, PEN_M	0.1108000E+08	0.000000
MAT_PROD_PORT_CUST(STARCH, SIBU, SGP)	2500000.	0.000000
MAT_PROD_PORT_CUST(STARCH, SIBU, THAI)	1000000.	0.000000
MAT_PROD_PORT_CUST(STARCH, MIRI, JAPAN	0.000000	0.000000
MAT_PROD_PORT_CUST(STARCH, MIRI, PEN_M	0.000000	0.000000
MAT_PROD_PORT_CUST(STARCH, MIRI, SGP)	0.000000	0.000000
MAT_PROD_PORT_CUST(STARCH, MIRI, THAI)	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, MUKAH_A, KUC	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, MUKAH_A, SMR	0.000000	0.000000

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DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, SRN        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, SMJ        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, SRA        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, BTG        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, SRT        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, SRK        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, MRD        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, SB)        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, DLT        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, MKH        76.00000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, TTU        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, BTL        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_A, MR)        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, KUC        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, SMR        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, SRN        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, SMJ        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, SRA        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, BTG        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, SRT        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, SRK        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, MRD        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, SB)        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, DLT        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, MKH        61.00000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, TTU        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, BTL        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, MUKAH_B, MR)        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, KUC        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, SMR        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, SRN        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, SMJ        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, SRA        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, BTG        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, SRT        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, SRK        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, MRD        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, SB)        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, DLT        63.00000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, MKH        14.00000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, TTU        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, BTL        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_A, MR)        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, KUC        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, SMR        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, SRN        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, SMJ        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, SRA        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, BTG        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, SRT        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, SRK        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, MRD        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, SB)        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, DLT        70.00000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, MKH        14.00000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, TTU        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, BTL        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_B, MR)        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_C, KUC        0.000000              0.000000
DIS_PLANT_MILL_DIS( MUKAH, DALAT_C, SMR        0.000000              0.000000
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DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, SRN	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, SMJ	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, SRA	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, BTG	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, SRT	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, SRK	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, MRD	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, SB)	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, DLT	58.00000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, MKH	14.00000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, TTU	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, BTL	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, DALAT_C, MR)	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, KUCH)	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, SMRH)	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, SRN)	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, SMJ)	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, SRAM)	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, BTG)	19.00000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, SRT)	27.00000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, SRK)	62.00000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, MRD)	28.00000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, SB)	55.00000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, DLT)	23.00000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, MKH)	14.00000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, TTU)	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, BTL)	0.000000	0.000000
DIS_PLANT_MILL_DIS(MUKAH, PUSA, MR)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, KUC	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, SMR	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, SRN	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, SMJ	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, SRA	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, BTG	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, SRT	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, SRK	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, MRD	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, SB)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, DLT	13.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, MKH	76.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, TTU	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, BTL	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_A, MR)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, KUC	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, SMR	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, SRN	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, SMJ	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, SRA	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, BTG	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, SRT	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, SRK	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, MRD	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, SB)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, DLT	13.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, MKH	61.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, TTU	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, BTL	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, MUKAH_B, MR)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, KUC	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, SMR	0.000000	0.000000

DIS_PLANT_MILL_DIS(DALAT, DALAT_A, SRN	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, SMJ	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, SRA	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, BTG	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, SRT	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, SRK	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, MRD	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, SB)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, DLT	63.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, MKH	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, TTU	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, BTL	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_A, MR)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, KUC	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, SMR	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, SRN	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, SMJ	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, SRA	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, BTG	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, SRT	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, SRK	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, MRD	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, SB)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, DLT	70.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, MKH	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, TTU	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, BTL	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_B, MR)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, KUC	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, SMR	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, SRN	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, SMJ	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, SRA	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, BTG	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, SRT	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, SRK	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, MRD	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, SB)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, DLT	58.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, MKH	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, TTU	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, BTL	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, DALAT_C, MR)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, KUCH)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, SMRH)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, SRN)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, SMJ)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, SRAM)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, BTG)	19.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, SRT)	27.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, SRK)	62.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, MRD)	28.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, SB)	55.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, DLT)	11.00000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, MKH)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, TTU)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, BTL)	0.000000	0.000000
DIS_PLANT_MILL_DIS(DALAT, PUSA, MR)	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, MUKAH_A, K	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, MUKAH_A, S	0.000000	0.000000

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DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, B        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, S        7.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, S        62.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, M        28.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, S        55.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, D        23.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, M        76.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, T        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, B        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_A, M        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, K        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, B        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, S        7.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, S        62.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, M        28.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, S        55.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, D        23.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, M        61.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, T        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, B        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, MUKAH_B, M        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, K        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, B        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, S        12.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, S        62.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, M        28.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, S        55.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, D        14.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, M        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, T        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, B        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_A, M        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, K        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, S        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, B        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, S        12.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, S        62.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, M        28.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, S        55.00000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, D        7.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, M        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, T        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, B        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_B, M        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_C, K        0.000000             0.000000
DIS_PLANT_MILL_DIS( SARATOK, DALAT_C, S        0.000000             0.000000
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DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, S	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, S	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, S	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, B	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, S	12.00000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, S	62.00000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, M	28.00000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, S	55.00000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, D	19.00000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, M	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, T	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, B	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, DALAT_C, M	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, KUCH	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, SMRH	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, SRN)	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, SMJ)	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, SRAM	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, BTG)	19.00000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, SRT)	27.00000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, SRK)	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, MRD)	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, SB)	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, DLT)	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, MKH)	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, TTU)	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, BTL)	0.000000	0.000000
DIS_PLANT_MILL_DIS(SARATOK, PUSA, MR)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, KU	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, SM	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, SR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, SM	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, SR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, BT	33.40000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, SR	27.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, SR	62.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, MR	28.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, SB	55.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, DL	23.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, MK	76.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, TT	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, BT	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_A, MR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, KU	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, SM	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, SR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, SM	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, SR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, BT	33.40000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, SR	27.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, SR	62.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, MR	28.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, SB	55.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, DL	23.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, MK	61.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, TT	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, BT	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, MUKAH_B, MR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, KU	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, SM	0.000000	0.000000

DIS_PLANT_MILL_DIS(BETONG, DALAT_A, SR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, SM	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, SR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, BT	33.40000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, SR	27.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, SR	62.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, MR	28.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, SB	55.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, DL	14.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, MK	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, TT	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, BT	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_A, MR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, KU	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, SM	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, SR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, SM	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, SR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, BT	33.40000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, SR	27.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, SR	62.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, MR	28.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, SB	55.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, DL	7.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, MK	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, TT	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, BT	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_B, MR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, KU	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, SM	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, SR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, SM	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, SR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, BT	33.40000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, SR	27.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, SR	62.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, MR	28.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, SB	55.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, DL	19.00000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, MK	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, TT	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, BT	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, DALAT_C, MR	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, KUCH)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, SMRH)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, SRN)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, SMJ)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, SRAM)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, BTG)	56.30000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, SRT)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, SRK)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, MRD)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, SB)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, DLT)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, MKH)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, TTU)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, BTL)	0.000000	0.000000
DIS_PLANT_MILL_DIS(BETONG, PUSA, MR)	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, MUKAH_A, KU	8.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, MUKAH_A, SM	12.00000	0.000000

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DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, SR        84.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, SM        18.50000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, SR        110.0000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, BT        10.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, SR        27.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, SR        62.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, MR        28.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, SB        55.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, DL        23.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, MK        76.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, TT        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, BT        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_A, MR        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, KU        8.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, SM        12.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, SR        84.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, SM        18.50000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, SR        110.0000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, BT        10.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, SR        27.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, SR        62.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, MR        28.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, SB        55.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, DL        23.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, MK        61.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, TT        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, BT        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, MUKAH_B, MR        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, KU        8.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, SM        12.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, SR        84.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, SM        18.50000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, SR        110.0000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, BT        10.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, SR        27.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, SR        62.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, MR        28.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, SB        55.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, DL        14.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, MK        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, TT        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, BT        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_A, MR        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, KU        8.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, SM        12.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, SR        84.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, SM        18.50000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, SR        110.0000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, BT        10.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, SR        27.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, SR        62.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, MR        28.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, SB        55.00000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, DL        7.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, MK        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, TT        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, BT        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_B, MR        0.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_C, KU        8.000000                  0.000000
DIS_MILL_PORT_DIS( KUCHING, DALAT_C, SM        12.00000                  0.000000
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DIS_MILL_PORT_DIS(KUCHING, DALAT_C, SR	84.00000	0.000000
DIS_MILL_PORT_DIS(KUCHING, DALAT_C, SM	18.50000	0.000000
DIS_MILL_PORT_DIS(KUCHING, DALAT_C, SR	110.0000	0.000000
DIS_MILL_PORT_DIS(KUCHING, DALAT_C, BT	10.00000	0.000000
DIS_MILL_PORT_DIS(KUCHING, DALAT_C, SR	27.00000	0.000000
DIS_MILL_PORT_DIS(KUCHING, DALAT_C, SR	62.00000	0.000000
DIS_MILL_PORT_DIS(KUCHING, DALAT_C, MR	28.00000	0.000000
DIS_MILL_PORT_DIS(KUCHING, DALAT_C, SB	55.00000	0.000000
DIS_MILL_PORT_DIS(KUCHING, DALAT_C, DL	19.00000	0.000000
DIS_MILL_PORT_DIS(KUCHING, DALAT_C, MK	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, DALAT_C, TT	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, DALAT_C, BT	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, DALAT_C, MR	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, KUCH)	8.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, SMRH)	12.00000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, SRN)	84.00000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, SMJ)	18.50000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, SRAM)	110.0000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, BTG)	56.30000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, SRT)	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, SRK)	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, MRD)	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, SB)	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, DLT)	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, MKH)	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, TTU)	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, BTL)	0.000000	0.000000
DIS_MILL_PORT_DIS(KUCHING, PUSA, MR)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, KUCH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, SMRH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, SRN)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, SMJ)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, SRAM)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, BTG)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, SRT)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, SRK)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, MRD)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, SB)	39.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, DLT)	23.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, MKH)	76.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, TTU)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, BTL)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_A, MR)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, KUCH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, SMRH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, SRN)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, SMJ)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, SRAM)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, BTG)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, SRT)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, SRK)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, MRD)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, SB)	39.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, DLT)	23.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, MKH)	61.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, TTU)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, BTL)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, MUKAH_B, MR)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, KUCH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, SMRH)	0.000000	0.000000

DIS_MILL_PORT_DIS(SIBU, DALAT_A, SRN)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, SMJ)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, SRAM)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, BTG)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, SRT)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, SRK)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, MRD)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, SB)	39.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, DLT)	14.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, MKH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, TTU)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, BTL)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_A, MR)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, KUCH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, SMRH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, SRN)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, SMJ)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, SRAM)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, BTG)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, SRT)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, SRK)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, MRD)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, SB)	39.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, DLT)	7.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, MKH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, TTU)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, BTL)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_B, MR)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, KUCH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, SMRH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, SRN)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, SMJ)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, SRAM)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, BTG)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, SRT)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, SRK)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, MRD)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, SB)	39.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, DLT)	19.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, MKH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, TTU)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, BTL)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, DALAT_C, MR)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, KUCH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, SMRH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, SRN)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, SMJ)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, SRAM)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, BTG)	19.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, SRT)	27.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, SRK)	62.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, MRD)	28.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, SB)	55.00000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, DLT)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, MKH)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, TTU)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, BTL)	0.000000	0.000000
DIS_MILL_PORT_DIS(SIBU, PUSA, MR)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, KUCH)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, SMRH)	0.000000	0.000000

DIS_MILL_PORT_DIS(MIRI, MUKAH_A, SRN)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, SMJ)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, SRAM)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, BTG)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, SRT)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, SRK)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, MRD)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, SB)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, DLT)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, MKH)	137.0000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, TTU)	34.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, BTL)	92.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_A, MR)	151.0000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, KUCH)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, SMRH)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, SRN)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, SMJ)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, SRAM)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, BTG)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, SRT)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, SRK)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, MRD)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, SB)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, DLT)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, MKH)	122.0000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, TTU)	34.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, BTL)	92.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, MUKAH_B, MR)	151.0000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, KUCH)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, SMRH)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, SRN)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, SMJ)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, SRAM)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, BTG)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, SRT)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, SRK)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, MRD)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, SB)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, DLT)	9.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, MKH)	72.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, TTU)	34.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, BTL)	92.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_A, MR)	151.0000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, KUCH)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, SMRH)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, SRN)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, SMJ)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, SRAM)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, BTG)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, SRT)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, SRK)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, MRD)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, SB)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, DLT)	16.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, MKH)	72.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, TTU)	34.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, BTL)	92.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_B, MR)	151.0000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, KUCH)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, SMRH)	0.000000	0.000000

DIS_MILL_PORT_DIS(MIRI, DALAT_C, SRN)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, SMJ)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, SRAM)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, BTG)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, SRT)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, SRK)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, MRD)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, SB)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, DLT)	4.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, MKH)	72.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, TTU)	34.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, BTL)	92.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, DALAT_C, MR)	151.0000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, KUCH)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, SMRH)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, SRN)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, SMJ)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, SRAM)	0.000000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, BTG)	19.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, SRT)	27.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, SRK)	62.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, MRD)	28.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, SB)	55.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, DLT)	24.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, MKH)	72.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, TTU)	34.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, BTL)	92.00000	0.000000
DIS_MILL_PORT_DIS(MIRI, PUSA, MR)	151.0000	0.000000
QLT_WW_OUT_PPM(LOG, MUKAH_A, STARCH, B	2900.000	0.000000
QLT_WW_OUT_PPM(LOG, MUKAH_A, STARCH, C	5600.000	0.000000
QLT_WW_OUT_PPM(LOG, MUKAH_A, STARCH, T	4500.000	0.000000
QLT_WW_OUT_PPM(LOG, MUKAH_A, STARCH, T	83.00000	0.000000
QLT_WW_OUT_PPM(LOG, MUKAH_B, STARCH, B	4000.000	0.000000
QLT_WW_OUT_PPM(LOG, MUKAH_B, STARCH, C	7000.000	0.000000
QLT_WW_OUT_PPM(LOG, MUKAH_B, STARCH, T	4650.000	0.000000
QLT_WW_OUT_PPM(LOG, MUKAH_B, STARCH, T	90.00000	0.000000
QLT_WW_OUT_PPM(LOG, DALAT_A, STARCH, B	3300.000	0.000000
QLT_WW_OUT_PPM(LOG, DALAT_A, STARCH, C	6000.000	0.000000
QLT_WW_OUT_PPM(LOG, DALAT_A, STARCH, T	4200.000	0.000000
QLT_WW_OUT_PPM(LOG, DALAT_A, STARCH, T	88.00000	0.000000
QLT_WW_OUT_PPM(LOG, DALAT_B, STARCH, B	3000.000	0.000000
QLT_WW_OUT_PPM(LOG, DALAT_B, STARCH, C	5800.000	0.000000
QLT_WW_OUT_PPM(LOG, DALAT_B, STARCH, T	4000.000	0.000000
QLT_WW_OUT_PPM(LOG, DALAT_B, STARCH, T	85.00000	0.000000
QLT_WW_OUT_PPM(LOG, DALAT_C, STARCH, B	3500.000	0.000000
QLT_WW_OUT_PPM(LOG, DALAT_C, STARCH, C	6500.000	0.000000
QLT_WW_OUT_PPM(LOG, DALAT_C, STARCH, T	4500.000	0.000000
QLT_WW_OUT_PPM(LOG, DALAT_C, STARCH, T	92.00000	0.000000
QLT_WW_OUT_PPM(LOG, PUSA, STARCH, BOD)	2650.000	0.000000
QLT_WW_OUT_PPM(LOG, PUSA, STARCH, COD)	5520.000	0.000000
QLT_WW_OUT_PPM(LOG, PUSA, STARCH, TSS)	3900.000	0.000000
QLT_WW_OUT_PPM(LOG, PUSA, STARCH, TKN)	80.00000	0.000000
QLT_WW_OUT_KG(LOG, MUKAH_A, STARCH, BO	76.85000	0.000000
QLT_WW_OUT_KG(LOG, MUKAH_A, STARCH, CO	148.4000	0.000000
QLT_WW_OUT_KG(LOG, MUKAH_A, STARCH, TS	119.2500	0.000000
QLT_WW_OUT_KG(LOG, MUKAH_A, STARCH, TK	2.199500	0.000000
QLT_WW_OUT_KG(LOG, MUKAH_B, STARCH, BO	120.0000	0.000000
QLT_WW_OUT_KG(LOG, MUKAH_B, STARCH, CO	210.0000	0.000000
QLT_WW_OUT_KG(LOG, MUKAH_B, STARCH, TS	139.5000	0.000000
QLT_WW_OUT_KG(LOG, MUKAH_B, STARCH, TK	2.700000	0.000000

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QLT_WW_OUT_KG( LOG, DALAT_A, STARCH, BO        95.04000              0.000000
QLT_WW_OUT_KG( LOG, DALAT_A, STARCH, CO        172.8000              0.000000
QLT_WW_OUT_KG( LOG, DALAT_A, STARCH, TS        120.9600              0.000000
QLT_WW_OUT_KG( LOG, DALAT_A, STARCH, TK        2.534400              0.000000
QLT_WW_OUT_KG( LOG, DALAT_B, STARCH, BO        81.00000              0.000000
QLT_WW_OUT_KG( LOG, DALAT_B, STARCH, CO        156.6000              0.000000
QLT_WW_OUT_KG( LOG, DALAT_B, STARCH, TS        108.0000              0.000000
QLT_WW_OUT_KG( LOG, DALAT_B, STARCH, TK        2.295000              0.000000
QLT_WW_OUT_KG( LOG, DALAT_C, STARCH, BO        101.5000              0.000000
QLT_WW_OUT_KG( LOG, DALAT_C, STARCH, CO        188.5000              0.000000
QLT_WW_OUT_KG( LOG, DALAT_C, STARCH, TS        130.5000              0.000000
QLT_WW_OUT_KG( LOG, DALAT_C, STARCH, TK        2.668000              0.000000
 QLT_WW_OUT_KG( LOG, PUSA, STARCH, BOD)        63.86500              0.000000
 QLT_WW_OUT_KG( LOG, PUSA, STARCH, COD)        133.0320              0.000000
 QLT_WW_OUT_KG( LOG, PUSA, STARCH, TSS)        93.99000              0.000000
 QLT_WW_OUT_KG( LOG, PUSA, STARCH, TKN)        1.928000              0.000000
 UFP_H2O_GW( LOG, MUKAH_A, STARCH, BOD)        1537.000              0.000000
 UFP_H2O_GW( LOG, MUKAH_A, STARCH, COD)        742.0000              0.000000
 UFP_H2O_GW( LOG, MUKAH_A, STARCH, TSS)        1192.500              0.000000
 UFP_H2O_GW( LOG, MUKAH_A, STARCH, TKN)        109.9750              0.000000
 UFP_H2O_GW( LOG, MUKAH_B, STARCH, BOD)        2400.000              0.000000
 UFP_H2O_GW( LOG, MUKAH_B, STARCH, COD)        1050.000              0.000000
 UFP_H2O_GW( LOG, MUKAH_B, STARCH, TSS)        1395.000              0.000000
 UFP_H2O_GW( LOG, MUKAH_B, STARCH, TKN)        135.0000              0.000000
 UFP_H2O_GW( LOG, DALAT_A, STARCH, BOD)        1900.800              0.000000
 UFP_H2O_GW( LOG, DALAT_A, STARCH, COD)        864.0000              0.000000
 UFP_H2O_GW( LOG, DALAT_A, STARCH, TSS)        1209.600              0.000000
 UFP_H2O_GW( LOG, DALAT_A, STARCH, TKN)        126.7200              0.000000
 UFP_H2O_GW( LOG, DALAT_B, STARCH, BOD)        1620.000              0.000000
 UFP_H2O_GW( LOG, DALAT_B, STARCH, COD)        783.0000              0.000000
 UFP_H2O_GW( LOG, DALAT_B, STARCH, TSS)        1080.000              0.000000
 UFP_H2O_GW( LOG, DALAT_B, STARCH, TKN)        114.7500              0.000000
 UFP_H2O_GW( LOG, DALAT_C, STARCH, BOD)        2030.000              0.000000
 UFP_H2O_GW( LOG, DALAT_C, STARCH, COD)        942.5000              0.000000
 UFP_H2O_GW( LOG, DALAT_C, STARCH, TSS)        1305.000              0.000000
 UFP_H2O_GW( LOG, DALAT_C, STARCH, TKN)        133.4000              0.000000
    UFP_H2O_GW( LOG, PUSA, STARCH, BOD)        1277.300              0.000000
    UFP_H2O_GW( LOG, PUSA, STARCH, COD)        665.1600              0.000000
    UFP_H2O_GW( LOG, PUSA, STARCH, TSS)        939.9000              0.000000
    UFP_H2O_GW( LOG, PUSA, STARCH, TKN)        96.40000              0.00000
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APPENDIX C

LINGO FILES AND RESULTS OF CHAPTER 5

CHAPTER 5

MATERIAL FLOW COST ACCOUNTING (MFCA)-BASED APPROACH FOR PRIORITISATION OF WASTE RECOVERY

Coding of Case Study:

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!TOTAL DESIRED PRODUCT PRODUCED IN EACH PROCESSING STEP, (ton);
TOT_DProd_WTP = DProd_WTP;
TOT_DProd_DBK = DProd_DBK;
TOT_DProd_RPG = DProd_RPG;
TOT_DProd_FSEP = DProd_FSEP;
TOT_DProd_SIEV = DProd_SIEV;
TOT_DProd_SWSEP = DProd_SWSEP;
TOT_DProd_FILT = DProd_FILT;
TOT_DProd_DRYPACK = DProd_SAST_DRYPACK;

!DESIRED PRODUCT PRODUCED IN EACH PROCESSING STEP, (ton);
DProd_WTP = 0;
DProd_DBK = 0;
DProd_RPG = 0;
DProd_FSEP = 0;
DProd_SIEV = 0;
DProd_SWSEP = 0;
DProd_FILT = 0;
DProd_SAST_DRYPACK = 12;

!TOTAL INTERMEDIATE PRODUCTS PRODUCED IN EACH PROCESSING STEP, (ton);
TOT_INTPROD_WTP = INTPROD_WTP_RPG + INTPROD_WTP_FSEP +
INTPROD_WTP_SIEV;
TOT_INTPROD_DBK = INTPROD_DBK_RPG;
TOT_INTPROD_RPG = INTPROD_RPG_FSEP;
TOT_INTPROD_FSEP = INTPROD_FSEP_SIEV;
TOT_INTPROD_SIEV = INTPROD_SIEV_SWSEP;
TOT_INTPROD_SWSEP = INTPROD_SWSEP_FILT;
TOT_INTPROD_FILT = INTPROD_FILT_DRYPACK;
TOT_INTPROD_DRYPACK = 0;

!INTERMEDIATE PRODUCTS PRODUCED IN EACH PROCESSING STEP, (ton);
INTPROD_WTP_RPG = 36.0;
INTPROD_WTP_FSEP = 87.0;
INTPROD_WTP_SIEV = 120.0;
INTPROD_DBK_RPG = 62.4;
INTPROD_RPG_FSEP = 98.4;
INTPROD_FSEP_SIEV = 91.3;
INTPROD_SIEV_SWSEP = 90.1;
INTPROD_SWSEP_FILT = 30.4;
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INTPROD_FILT_DRYPACK = 12.5;
INTPROD_DRYPACK = 0;

!WASTES GENERATED IN EACH PROCESSING STEP, (ton);
TOT_WASTE_WTP = WASTE_WTP;
TOT_WASTE_DBK = WASTE_BARK_DBK;
TOT_WASTE_RPG = WASTE_RPG;
TOT_WASTE_FSEP = WASTE_WW_FSEP + WASTE_HPS_FSEP;
TOT_WASTE_SIEV = WASTE_WW_SIEV + WASTE_HPS_SIEV;
TOT_WASTE_SWSEP = WASTE_WW_SWSEP;
TOT_WASTE_FILT = WASTE_WW_FILT;
TOT_WASTE_DRYPACK = WASTE_DRYPACK;

!WASTES GENERATED IN EACH PROCESSING STEP, (person);
WASTE_WTP = 0;
WASTE_BARK_DBK = 20.8;
WASTE_RPG = 0;
WASTE_WW_FSEP = 79.0;
WASTE_HPS_FSEP = 15.1;
WASTE_WW_SIEV = 119.4;
WASTE_HPS_SIEV = 1.8;
WASTE_WW_SWSEP = 59.7;
WASTE_WW_FILT = 17.9;
WASTE_DRYPACK = 0;

!RAW MATERIAL REQUIRED IN EACH PROCESSING STEP, (ton);
RAWMAT_WATER_WTP = 243 - (WASTE_RECY_WW_FSEP_WTP +
WASTE_RECY_WW_SIEV_WTP + WASTE_RECY_WW_SWSEP_WTP +
WASTE_RECY_WW_FILT_WTP) ; !ton;
RAWMAT_LOG_DBK = 832;    !log;
RAWMAT_RPG = 0;
RAWMAT_FSEP = 0;
RAWMAT_SIEV = 0;
RAWMAT_SWSEP = 0;
RAWMAT_FILT = 0;
RAWMAT_DRYPACK = 0;

!ENERGY REQUIRED IN EACH PROCESSING STEP, (kWh);
ENERGY_ELEC_WTP = 110;
ENERGY_ELEC_DBK = 20;
ENERGY_ELEC_RPG = 445;
ENERGY_ELEC_FSEP = 440;
ENERGY_ELEC_SIEV = 295;
ENERGY_ELEC_SWSEP = 330;
ENERGY_ELEC_FILT = 55;
ENERGY_ELEC_DRYPACK = 250;

!MANPOWER REQUIRED IN EACH PROCESSING STEP, (person);
LABOUR_LOCAL_WTP = 1;
LABOUR_LOCAL_DBK = 3;
LABOUR_LOCAL_RPG = 6;
LABOUR_LOCAL_FSEP = 1;
LABOUR_LOCAL_SIEV = 1;
LABOUR_LOCAL_SWSEP = 1;
LABOUR_LOCAL_FILT = 1;
LABOUR_LOCAL_DRYPACK = 3;

!UNIT COST OF RAW MATERIAL;
UCOST_RAWMAT_WATER = 0.33; !(USD/M3);
UCOST_RAWMAT_LOG = 2.8;!(USD/LOG);
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!UNIT COST OF ENERGY;
UCOST_ENERGY_ELEC = 0.11; !(USD/UNIT);

!UNIT COST OF LABOUR;
UCOST_LABOUR_LOCAL = 8.0; !(USD/DAY/PERSON);

!UNIT COST OF WASTE DISPOSAL,(USD/KG);
UCOST_WASTE_BOD = 0.02;
UCOST_WASTE_NH3N = 15.63;

!TOTAL COST OF RAW MATERIAL;
TOTCOST_RAWMAT_WTP = RAWMAT_WATER_WTP * UCOST_RAWMAT_WATER;
TOTCOST_RAWMAT_DBK = RAWMAT_LOG_DBK * UCOST_RAWMAT_LOG;

TOTCOST_RAWMAT = TOTCOST_RAWMAT_WTP + TOTCOST_RAWMAT_DBK;

!TOTAL COST OF ENERGY;
TOTCOST_ENERGY_WTP = ENERGY_ELEC_WTP * UCOST_ENERGY_ELEC;
TOTCOST_ENERGY_DBK = ENERGY_ELEC_DBK * UCOST_ENERGY_ELEC;
TOTCOST_ENERGY_RPG = ENERGY_ELEC_RPG * UCOST_ENERGY_ELEC;
TOTCOST_ENERGY_FSEP = ENERGY_ELEC_FSEP * UCOST_ENERGY_ELEC;
TOTCOST_ENERGY_SIEV = ENERGY_ELEC_SIEV * UCOST_ENERGY_ELEC;
TOTCOST_ENERGY_SWSEP = ENERGY_ELEC_SWSEP * UCOST_ENERGY_ELEC;
TOTCOST_ENERGY_FILT = ENERGY_ELEC_FILT * UCOST_ENERGY_ELEC;
TOTCOST_ENERGY_DRYPACK = ENERGY_ELEC_DRYPACK * UCOST_ENERGY_ELEC;

TOTCOST_ENERGY = TOTCOST_ENERGY_WTP + TOTCOST_ENERGY_DBK +
TOTCOST_ENERGY_RPG + TOTCOST_ENERGY_FSEP + TOTCOST_ENERGY_SIEV +
TOTCOST_ENERGY_SWSEP + TOTCOST_ENERGY_FILT + TOTCOST_ENERGY_DRYPACK;

!TOTAL COST OF LOBOUR;
TOTCOST_LABOUR_WTP = LABOUR_LOCAL_WTP * UCOST_LABOUR_LOCAL;
TOTCOST_LABOUR_DBK = LABOUR_LOCAL_DBK * UCOST_LABOUR_LOCAL;
TOTCOST_LABOUR_RPG = LABOUR_LOCAL_RPG * UCOST_LABOUR_LOCAL;
TOTCOST_LABOUR_FSEP = LABOUR_LOCAL_FSEP * UCOST_LABOUR_LOCAL;
TOTCOST_LABOUR_SIEV = LABOUR_LOCAL_SIEV * UCOST_LABOUR_LOCAL;
TOTCOST_LABOUR_SWSEP = LABOUR_LOCAL_SWSEP * UCOST_LABOUR_LOCAL;
TOTCOST_LABOUR_FILT = LABOUR_LOCAL_FILT * UCOST_LABOUR_LOCAL;
TOTCOST_LABOUR_DRYPACK = LABOUR_LOCAL_DRYPACK * UCOST_LABOUR_LOCAL;

TOTCOST_LABOUR = TOTCOST_LABOUR_WTP + TOTCOST_LABOUR_DBK +
TOTCOST_LABOUR_RPG + TOTCOST_LABOUR_FSEP + TOTCOST_LABOUR_SIEV +
TOTCOST_LABOUR_SWSEP + TOTCOST_LABOUR_FILT + TOTCOST_LABOUR_DRYPACK;

!TOTAL COST OF WASTE DISPOSAL;
!Input Waste Quality of wastewater (included hampas), (mg/l or g/m3);
BOD_FSEP = 5360.5;
BOD_SIEV = 2497.0;
BOD_SWSEP = 2534.4;
BOD_FILT = 2816.0;

NH3N_FSEP = 93.4;
NH3N_SIEV = 43.5;
NH3N_SWSEP = 44.2;
NH3N_FILT = 49.1;

!DOE specification of stardard A, (mg/l or g/m3);
DOE_BOD_A = 20;
DOE_NH3N_A = 10;
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TOTCOST_WASTE_FSEP = (((TOT_WASTE_FSEP - WASTE_RECY_WW_FSEP_WTP) *
(BOD_FSEP - DOE_BOD_A) / 1000) * UCOST_WASTE_BOD) +
(((TOT_WASTE_FSEP - WASTE_RECY_WW_FSEP_WTP) * (NH3N_FSEP -
DOE_NH3N_A) / 1000) * UCOST_WASTE_NH3N);
TOTCOST_WASTE_SIEV = (((TOT_WASTE_SIEV - WASTE_RECY_WW_SIEV_WTP) *
(BOD_SIEV - DOE_BOD_A) / 1000) * UCOST_WASTE_BOD) +
(((TOT_WASTE_SIEV - WASTE_RECY_WW_SIEV_WTP) * (NH3N_SIEV -
DOE_NH3N_A) / 1000) * UCOST_WASTE_NH3N);
TOTCOST_WASTE_SWSEP = (((TOT_WASTE_SWSEP - WASTE_RECY_WW_SWSEP_WTP)
* (BOD_SWSEP - DOE_BOD_A) / 1000) * UCOST_WASTE_BOD) +
(((TOT_WASTE_SWSEP - WASTE_RECY_WW_SWSEP_WTP) * (NH3N_SWSEP -
DOE_NH3N_A) / 1000) * UCOST_WASTE_NH3N);
TOTCOST_WASTE_FILT = (((TOT_WASTE_FILT - WASTE_RECY_WW_FILT_WTP) *
(BOD_FILT - DOE_BOD_A) / 1000) * UCOST_WASTE_BOD) +
(((TOT_WASTE_FILT - WASTE_RECY_WW_FILT_WTP) * (NH3N_FILT -
DOE_NH3N_A) / 1000) * UCOST_WASTE_NH3N);

TOTCOST_WASTE = TOTCOST_WASTE_FSEP + TOTCOST_WASTE_SIEV +
TOTCOST_WASTE_SWSEP + TOTCOST_WASTE_FILT;

!PROCESSING COST OF EACH PROCESSING STEP;
PC_WTP = TOTCOST_RAWMAT_WTP + TOTCOST_ENERGY_WTP +
TOTCOST_LABOUR_WTP;
PC_DBK = TOTCOST_RAWMAT_DBK + TOTCOST_ENERGY_DBK +
TOTCOST_LABOUR_DBK;
PC_RPG = TOTCOST_ENERGY_RPG + TOTCOST_LABOUR_RPG;
PC_FSEP = TOTCOST_ENERGY_FSEP + TOTCOST_LABOUR_FSEP;
PC_SIEV = TOTCOST_ENERGY_SIEV + TOTCOST_LABOUR_SIEV;
PC_SWSEP = TOTCOST_ENERGY_SWSEP + TOTCOST_LABOUR_SWSEP;
PC_FILT = TOTCOST_ENERGY_FILT + TOTCOST_LABOUR_FILT;
PC_DRYPACK = TOTCOST_ENERGY_DRYPACK + TOTCOST_LABOUR_DRYPACK;

!TOTAL OUTPUT OF EACH PROCESSING STEP;
OUTPUT_WTP = TOT_DProd_WTP + TOT_INTPROD_WTP + TOT_WASTE_WTP;
OUTPUT_DBK = TOT_DProd_DBK + TOT_INTPROD_DBK  + TOT_WASTE_DBK;
OUTPUT_RPG = TOT_DProd_RPG + TOT_INTPROD_RPG + TOT_WASTE_RPG;
OUTPUT_FSEP = TOT_DProd_FSEP + TOT_INTPROD_FSEP + TOT_WASTE_FSEP;
OUTPUT_SIEV = TOT_DProd_SIEV + TOT_INTPROD_SIEV + TOT_WASTE_SIEV;
OUTPUT_SWSEP = TOT_DProd_SWSEP + TOT_INTPROD_SWSEP + TOT_WASTE_SWSEP;
OUTPUT_FILT = TOT_DProd_FILT + TOT_INTPROD_FILT + TOT_WASTE_FILT;
OUTPUT_DRYPACK = TOT_DProd_DRYPACK + TOT_INTPROD_DRYPACK +
TOT_WASTE_DRYPACK;

!TOTAL ACTUAL PROCESSING COST (TAPC) OF EACH PROCESSING STEP;
TAPC_WTP = PC_WTP + CFC_WTP;
TAPC_DBK = PC_DBK + CFC_DBK;
TAPC_RPG = PC_RPG + CFC_RPG;
TAPC_FSEP = PC_FSEP + CFC_FSEP;
TAPC_SIEV = PC_SIEV + CFC_SIEV;
TAPC_SWSEP = PC_SWSEP + CFC_SWSEP;
TAPC_FILT = PC_FILT + CFC_FILT;
TAPC_DRYPACK = PC_DRYPACK + CFC_DRYPACK;

!CARRIED FORWARD COST (CFC) OF EACH PROCESSING STEP;
CFC_WTP = CFC_WW_FSEP_WTP + CFC_WW_SIEV_WTP + CFC_WW_SWSEP_WTP +
CFC_WW_FILT_WTP;
CFC_DBK = 0;
CFC_RPG = CFC_DBK_RPG + CFC_WTP_RPG;
CFC_FSEP = CFC_RPG_FSEP + CFC_WTP_FSEP;
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CFC_SIEV = CFC_FSEP_SIEV + CFC_WTP_SIEV;
CFC_SWSEP = CFC_SIEV_SWSEP;
CFC_FILT = CFC_SWSEP_FILT;
CFC_DRYPACK = CFC_FILT_DRYPACK;

CFC_WW_FSEP_WTP = (WASTE_RECY_WW_FSEP_WTP / OUTPUT_FSEP) * TAPC_FSEP;
CFC_WW_SIEV_WTP = (WASTE_RECY_WW_SIEV_WTP / OUTPUT_SIEV) * TAPC_SIEV;
CFC_WW_SWSEP_WTP = (WASTE_RECY_WW_SWSEP_WTP / OUTPUT_SWSEP) *
TAPC_SWSEP;
CFC_WW_FILT_WTP = (WASTE_RECY_WW_FILT_WTP / OUTPUT_FILT) * TAPC_FILT;

CFC_DBK_RPG = (INTPROD_DBK_RPG / OUTPUT_DBK)* TAPC_DBK;
CFC_WTP_RPG = (INTPROD_WTP_RPG / OUTPUT_WTP)* TAPC_WTP;
CFC_RPG_FSEP = (INTPROD_RPG_FSEP / OUTPUT_RPG) * TAPC_RPG;
CFC_WTP_FSEP = (INTPROD_WTP_FSEP / OUTPUT_WTP) * TAPC_WTP;
CFC_FSEP_SIEV =  (INTPROD_FSEP_SIEV / OUTPUT_FSEP) * TAPC_FSEP;
CFC_WTP_SIEV = (INTPROD_WTP_SIEV / OUTPUT_WTP) * TAPC_WTP;
CFC_SIEV_SWSEP = (INTPROD_SIEV_SWSEP / OUTPUT_SIEV) * TAPC_SIEV;
CFC_SWSEP_FILT = (INTPROD_SWSEP_FILT / OUTPUT_SWSEP) * TAPC_SWSEP;
CFC_FILT_DRYPACK = (INTPROD_FILT_DRYPACK /OUTPUT_FILT) * TAPC_FILT;


!TOTAL ACTUAL PROCESSING UNIT COST (TAPUC) OF EACH PROCESSING STEP;
TAPUC_DIS_WTP = TAPC_WTP/OUTPUT_WTP;
TAPUC_DIS_DBK = TAPC_DBK/OUTPUT_DBK;
TAPUC_DIS_RPG = TAPC_RPG/OUTPUT_RPG;
TAPUC_DIS_FSEP = TAPC_FSEP/OUTPUT_FSEP;
TAPUC_DIS_SIEV = TAPC_SIEV/OUTPUT_SIEV;
TAPUC_DIS_SWSEP = TAPC_SWSEP/OUTPUT_SWSEP;
TAPUC_DIS_FILT = TAPC_FILT/OUTPUT_FILT;
TAPUC_DIS_DRYPACK = TAPC_DRYPACK/OUTPUT_DRYPACK;

!TOTAL ACTUAL PROCESSING COST (TAPUC) OF DISCHARGED WASTE OF EACH
PROCESSING STEP;
TAPC_DIS_WTP = TAPUC_DIS_WTP * WASTE_DIS_WTP;
TAPC_DIS_DBK = TAPUC_DIS_DBK * WASTE_DIS_DBK;
TAPC_DIS_RPG = TAPUC_DIS_RPG * WASTE_DIS_RPG;
TAPC_DIS_FSEP = (TAPUC_DIS_FSEP * WASTE_DIS_FSEP)+
TOTCOST_WASTE_FSEP;
TAPC_DIS_SIEV = (TAPUC_DIS_SIEV * WASTE_DIS_SIEV)+
TOTCOST_WASTE_SIEV;
TAPC_DIS_SWSEP = (TAPUC_DIS_SWSEP * WASTE_DIS_SWSEP)+
TOTCOST_WASTE_SWSEP;
TAPC_DIS_FILT = (TAPUC_DIS_FILT * WASTE_DIS_FILT)+
TOTCOST_WASTE_FILT;
TAPC_DIS_DRYPACK = TAPUC_DIS_DRYPACK * WASTE_DIS_DRYPACK;

TOT_TAPC_DIS = TAPC_DIS_WTP + TAPC_DIS_DBK + TAPC_DIS_RPG +
TAPC_DIS_FSEP + TAPC_DIS_SIEV + TAPC_DIS_SWSEP + TAPC_DIS_FILT +
TAPC_DIS_DRYPACK;

!DISCHARGED WASTES AND RECYCLED WASTES IN EACH PROCESSING STEP,
(ton);
TOT_WASTE_WTP = WASTE_DIS_WTP + WASTE_RECY_WTP; ! NO WASTE GENERATED;
TOT_WASTE_DBK = WASTE_DIS_DBK + WASTE_RECY_DBK; WASTE_RECY_DBK = 0;
TOT_WASTE_RPG = WASTE_DIS_RPG + WASTE_RECY_RPG; ! NO WASTE GENERATED;
TOT_WASTE_FSEP = WASTE_DIS_FSEP + WASTE_RECY_FSEP_WTP;
TOT_WASTE_SIEV = WASTE_DIS_SIEV + WASTE_RECY_SIEV_WTP;
TOT_WASTE_SWSEP = WASTE_DIS_SWSEP + WASTE_RECY_SWSEP_WTP;
TOT_WASTE_FILT = WASTE_DIS_FILT + WASTE_RECY_FILT_WTP;
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TOT_WASTE_DRYPACK = WASTE_DIS_DRYPACK + WASTE_RECY_DRYPACK; ! NO
WASTE GENERATED;

!DISCHARGED WASTES AND RECYCLED WASTES IN HAMPAS SEPARATION, (ton);
WASTE_DIS_FSEP = WASTE_DIS_WW_FSEP + WASTE_DIS_HPS_FSEP;
WASTE_RECY_FSEP_WTP = WASTE_RECY_WW_FSEP_WTP +
WASTE_RECY_HPS_FSEP_WTP; WASTE_RECY_HPS_FSEP_WTP = 0;
!******* For Discussion Part; !WASTE_RECY_WW_FSEP_WTP = 6.61;

WASTE_WW_FSEP = WASTE_DIS_WW_FSEP + WASTE_RECY_WW_FSEP_WTP;
WASTE_HPS_FSEP = WASTE_DIS_HPS_FSEP + WASTE_RECY_HPS_FSEP_WTP;
WASTE_RECY_HPS_FSEP_WTP = 0;

!DISCHARGED WASTES AND RECYCLED WASTES IN SEIVING, (ton);
WASTE_DIS_SIEV = WASTE_DIS_WW_SIEV + WASTE_DIS_HPS_SIEV;
WASTE_RECY_SIEV_WTP = WASTE_RECY_WW_SIEV_WTP +
WASTE_RECY_HPS_SIEV_WTP; WASTE_RECY_HPS_SIEV_WTP = 0;
!******* For Discussion Part; !WASTE_RECY_WW_SIEV_WTP = 0;

WASTE_WW_SIEV = WASTE_DIS_WW_SIEV + WASTE_RECY_WW_SIEV_WTP;
WASTE_HPS_SIEV = WASTE_DIS_HPS_SIEV + WASTE_RECY_HPS_SIEV_WTP;
WASTE_RECY_HPS_SIEV_WTP = 0;

!DISCHARGED WASTES AND RECYCLED WASTES IN STARCH WATER SEPARATION,
(ton);
WASTE_DIS_SWSEP = WASTE_DIS_WW_SWSEP;
WASTE_RECY_SWSEP_WTP = WASTE_RECY_WW_SWSEP_WTP;
!******* For Discussion Part; !WASTE_RECY_WW_SWSEP_WTP = 0;

WASTE_WW_SWSEP = WASTE_DIS_WW_SWSEP + WASTE_RECY_WW_SWSEP_WTP;

!DISCHARGED WASTES AND RECYCLED WASTES IN FILTRATION, (ton);
WASTE_DIS_FILT = WASTE_DIS_WW_FILT;
WASTE_RECY_FILT_WTP = WASTE_RECY_WW_FILT_WTP;
!******* For Discussion Part; !WASTE_RECY_WW_FILT_WTP = 27.59;

WASTE_WW_FILT = WASTE_DIS_WW_FILT + WASTE_RECY_WW_FILT_WTP;

!RECYCLE RATIO (RR) FOR WATER TREATMENT PLANT (WTP);
RR_WW_WTP = (WASTE_RECY_WW_FSEP_WTP + WASTE_RECY_WW_SIEV_WTP +
WASTE_RECY_WW_SWSEP_WTP + WASTE_RECY_WW_FILT_WTP) / 276 ;

RR_WW_WTP = 0.88; !RR_WW_WTP = 0.00 - 0.88 (recycled percentage);
!RR_WW_WTP <= 1;

!WASTE_RECY_WW_FSEP_WTP = 0;
!WASTE_RECY_WW_FILT_WTP = 17.9;
!WASTE_RECY_WW_SWSEP_WTP = 59.7;
!WASTE_RECY_WW_SIEV_WTP = 119.4;

min = TOT_TAPC_DIS;
```

Results of Case Study:

```
Global optimal solution found.
Objective value:                              2250.509
Objective bound:                              2250.509
Infeasibilities:                            0.4263666E-07
Extended solver steps:                              25
Total solver iterations:                          6788

Model Class:                                       NLP

Total variables:                   72
Nonlinear variables:               22
Integer variables:                  0

Total constraints:                 73
Nonlinear constraints:             11

Total nonzeros:                   176
Nonlinear nonzeros:                22
```

Variable	Value	Reduced Cost
TOT_DPROD_WTP	0.000000	0.000000
DPROD_WTP	0.000000	0.000000
TOT_DPROD_DBK	0.000000	0.000000
DPROD_DBK	0.000000	0.000000
TOT_DPROD_RPG	0.000000	0.000000
DPROD_RPG	0.000000	0.000000
TOT_DPROD_FSEP	0.000000	0.000000
DPROD_FSEP	0.000000	0.000000
TOT_DPROD_SIEV	0.000000	0.000000
DPROD_SIEV	0.000000	0.000000
TOT_DPROD_SWSEP	0.000000	0.000000
DPROD_SWSEP	0.000000	0.000000
TOT_DPROD_FILT	0.000000	0.000000
DPROD_FILT	0.000000	0.000000
TOT_DPROD_DRYPACK	12.00000	0.000000
DPROD_SAST_DRYPACK	12.00000	0.000000
TOT_INTPROD_WTP	243.0000	0.000000
INTPROD_WTP_RPG	36.00000	0.000000
INTPROD_WTP_FSEP	87.00000	0.000000
INTPROD_WTP_SIEV	120.0000	0.000000
TOT_INTPROD_DBK	62.40000	0.000000
INTPROD_DBK_RPG	62.40000	0.000000
TOT_INTPROD_RPG	98.40000	0.000000
INTPROD_RPG_FSEP	98.40000	0.000000
TOT_INTPROD_FSEP	91.30000	0.000000
INTPROD_FSEP_SIEV	91.30000	0.000000
TOT_INTPROD_SIEV	90.10000	0.000000
INTPROD_SIEV_SWSEP	90.10000	0.000000
TOT_INTPROD_SWSEP	30.40000	0.000000
INTPROD_SWSEP_FILT	30.40000	0.000000
TOT_INTPROD_FILT	12.50000	0.000000
INTPROD_FILT_DRYPACK	12.50000	0.000000
TOT_INTPROD_DRYPACK	0.000000	0.000000
INTPROD_DRYPACK	0.000000	0.000000
TOT_WASTE_WTP	0.000000	0.000000
WASTE_WTP	0.000000	0.000000
TOT_WASTE_DBK	20.80000	0.000000

WASTE_BARK_DBK	20.80000	0.000000
TOT_WASTE_RPG	0.000000	0.000000
WASTE_RPG	0.000000	0.000000
TOT_WASTE_FSEP	94.10000	0.000000
WASTE_WW_FSEP	79.00000	0.000000
WASTE_HPS_FSEP	15.10000	0.000000
TOT_WASTE_SIEV	121.2000	0.000000
WASTE_WW_SIEV	119.4000	0.000000
WASTE_HPS_SIEV	1.800000	0.000000
TOT_WASTE_SWSEP	59.70000	0.000000
WASTE_WW_SWSEP	59.70000	0.000000
TOT_WASTE_FILT	17.90000	0.000000
WASTE_WW_FILT	17.90000	0.000000
TOT_WASTE_DRYPACK	0.000000	0.000000
WASTE_DRYPACK	0.000000	0.000000
RAWMAT_WATER_WTP	0.1200000	0.000000
WASTE_RECY_WW_FSEP_WTP	79.00000	0.000000
WASTE_RECY_WW_SIEV_WTP	86.28000	0.000000
WASTE_RECY_WW_SWSEP_WTP	59.70000	0.000000
WASTE_RECY_WW_FILT_WTP	17.90000	0.000000
RAWMAT_LOG_DBK	832.0000	0.000000
RAWMAT_RPG	0.000000	0.000000
RAWMAT_FSEP	0.000000	0.000000
RAWMAT_SIEV	0.000000	0.000000
RAWMAT_SWSEP	0.000000	0.000000
RAWMAT_FILT	0.000000	0.000000
RAWMAT_DRYPACK	0.000000	0.000000
ENERGY_ELEC_WTP	110.0000	0.000000
ENERGY_ELEC_DBK	20.00000	0.000000
ENERGY_ELEC_RPG	445.0000	0.000000
ENERGY_ELEC_FSEP	440.0000	0.000000
ENERGY_ELEC_SIEV	295.0000	0.000000
ENERGY_ELEC_SWSEP	330.0000	0.000000
ENERGY_ELEC_FILT	55.00000	0.000000
ENERGY_ELEC_DRYPACK	250.0000	0.000000
LABOUR_LOCAL_WTP	1.000000	0.000000
LABOUR_LOCAL_DBK	3.000000	0.000000
LABOUR_LOCAL_RPG	6.000000	0.000000
LABOUR_LOCAL_FSEP	1.000000	0.000000
LABOUR_LOCAL_SIEV	1.000000	0.000000
LABOUR_LOCAL_SWSEP	1.000000	0.000000
LABOUR_LOCAL_FILT	1.000000	0.000000
LABOUR_LOCAL_DRYPACK	3.000000	0.000000
UCOST_RAWMAT_WATER	0.3300000	0.000000
UCOST_RAWMAT_LOG	2.800000	0.000000
UCOST_ENERGY_ELEC	0.1100000	0.000000
UCOST_LABOUR_LOCAL	8.000000	0.000000
UCOST_WASTE_BOD	0.2000000E-01	0.000000
UCOST_WASTE_NH3N	15.63000	0.000000
TOTCOST_RAWMAT_WTP	0.3960000E-01	0.000000
TOTCOST_RAWMAT_DBK	2329.600	0.000000
TOTCOST_RAWMAT	2329.640	0.000000
TOTCOST_ENERGY_WTP	12.10000	0.000000
TOTCOST_ENERGY_DBK	2.200000	0.000000
TOTCOST_ENERGY_RPG	48.95000	0.000000
TOTCOST_ENERGY_FSEP	48.40000	0.000000
TOTCOST_ENERGY_SIEV	32.45000	0.000000
TOTCOST_ENERGY_SWSEP	36.30000	0.000000
TOTCOST_ENERGY_FILT	6.050000	0.000000
TOTCOST_ENERGY_DRYPACK	27.50000	0.000000

TOTCOST_ENERGY	213.9500	0.000000
TOTCOST_LABOUR_WTP	8.000000	0.000000
TOTCOST_LABOUR_DBK	24.00000	0.000000
TOTCOST_LABOUR_RPG	48.00000	0.000000
TOTCOST_LABOUR_FSEP	8.000000	0.000000
TOTCOST_LABOUR_SIEV	8.000000	0.000000
TOTCOST_LABOUR_SWSEP	8.000000	0.000000
TOTCOST_LABOUR_FILT	8.000000	0.000000
TOTCOST_LABOUR_DRYPACK	24.00000	0.000000
TOTCOST_LABOUR	136.0000	0.000000
BOD_FSEP	5360.500	0.000000
BOD_SIEV	2497.000	0.000000
BOD_SWSEP	2534.400	0.000000
BOD_FILT	2816.000	0.000000
NH3N_FSEP	93.40000	0.000000
NH3N_SIEV	43.50000	0.000000
NH3N_SWSEP	44.20000	0.000000
NH3N_FILT	49.10000	0.000000
DOE_BOD_A	20.00000	0.000000
DOE_NH3N_A	10.00000	0.000000
TOTCOST_WASTE_FSEP	21.29632	0.000000
TOTCOST_WASTE_SIEV	20.01422	0.000000
TOTCOST_WASTE_SWSEP	0.000000	0.000000
TOTCOST_WASTE_FILT	0.000000	0.000000
TOTCOST_WASTE	41.31054	0.000000
PC_WTP	20.13960	0.000000
PC_DBK	2355.800	0.000000
PC_RPG	96.95000	0.000000
PC_FSEP	56.40000	0.000000
PC_SIEV	40.45000	0.000000
PC_SWSEP	44.30000	0.000000
PC_FILT	14.05000	0.000000
PC_DRYPACK	51.50000	0.000000
OUTPUT_WTP	243.0000	0.000000
OUTPUT_DBK	83.20000	0.000000
OUTPUT_RPG	98.40000	0.000000
OUTPUT_FSEP	185.4000	0.000000
OUTPUT_SIEV	211.3000	0.000000
OUTPUT_SWSEP	90.10000	0.000000
OUTPUT_FILT	30.40000	0.000000
OUTPUT_DRYPACK	12.00000	0.000000
TAPC_WTP	7930.829	0.000000
CFC_WTP	7910.689	0.000000
TAPC_DBK	2355.800	0.000000
CFC_DBK	0.000000	0.000000
TAPC_RPG	3038.738	0.000000
CFC_RPG	2941.788	0.000000
TAPC_FSEP	5934.570	0.000000
CFC_FSEP	5878.170	0.000000
TAPC_SIEV	6879.381	0.000000
CFC_SIEV	6838.931	0.000000
TAPC_SWSEP	2977.723	0.000000
CFC_SWSEP	2933.423	0.000000
TAPC_FILT	1018.742	0.000000
CFC_FILT	1004.692	0.000000
TAPC_DRYPACK	470.3907	0.000000
CFC_DRYPACK	418.8907	0.000000
CFC_WW_FSEP_WTP	2528.754	0.000000
CFC_WW_SIEV_WTP	2809.053	0.000000
CFC_WW_SWSEP_WTP	1973.030	0.000000

CFC_WW_FILT_WTP	599.8515	0.000000
CFC_DBK_RPG	1766.850	0.000000
CFC_WTP_RPG	1174.938	0.000000
CFC_RPG_FSEP	3038.738	0.000000
CFC_WTP_FSEP	2839.433	0.000000
CFC_FSEP_SIEV	2922.472	0.000000
CFC_WTP_SIEV	3916.459	0.000000
CFC_SIEV_SWSEP	2933.423	0.000000
CFC_SWSEP_FILT	1004.692	0.000000
CFC_FILT_DRYPACK	418.8907	0.000000
TAPUC_DIS_WTP	32.63716	0.000000
TAPUC_DIS_DBK	28.31490	0.000000
TAPUC_DIS_RPG	30.88148	0.000000
TAPUC_DIS_FSEP	32.00955	0.000000
TAPUC_DIS_SIEV	32.55741	0.000000
TAPUC_DIS_SWSEP	33.04908	0.000000
TAPUC_DIS_FILT	33.51126	0.000000
TAPUC_DIS_DRYPACK	39.19922	0.000000
TAPC_DIS_WTP	0.000000	0.000000
WASTE_DIS_WTP	0.000000	32.63716
TAPC_DIS_DBK	588.9500	0.000000
WASTE_DIS_DBK	20.80000	0.000000
TAPC_DIS_RPG	0.000000	0.000000
WASTE_DIS_RPG	0.000000	30.88148
TAPC_DIS_FSEP	504.6405	0.000000
WASTE_DIS_FSEP	15.10000	0.000000
TAPC_DIS_SIEV	1156.919	0.000000
WASTE_DIS_SIEV	34.92000	0.000000
TAPC_DIS_SWSEP	0.000000	0.3437200E-02
WASTE_DIS_SWSEP	0.000000	0.000000
TAPC_DIS_FILT	0.000000	0.8646040E-02
WASTE_DIS_FILT	0.000000	0.000000
TAPC_DIS_DRYPACK	0.000000	0.000000
WASTE_DIS_DRYPACK	0.000000	39.19922
TOT_TAPC_DIS	2250.509	0.000000
WASTE_RECY_WTP	0.000000	0.000000
WASTE_RECY_DBK	0.000000	0.000000
WASTE_RECY_RPG	0.000000	0.000000
WASTE_RECY_FSEP_WTP	79.00000	0.000000
WASTE_RECY_SIEV_WTP	86.28000	0.000000
WASTE_RECY_SWSEP_WTP	59.70000	0.000000
WASTE_RECY_FILT_WTP	17.90000	0.000000
WASTE_RECY_DRYPACK	0.000000	0.000000
WASTE_DIS_WW_FSEP	0.000000	0.7214146
WASTE_DIS_HPS_FSEP	15.10000	0.000000
WASTE_RECY_HPS_FSEP_WTP	0.000000	0.000000
WASTE_DIS_WW_SIEV	33.12000	0.000000
WASTE_DIS_HPS_SIEV	1.800000	0.000000
WASTE_RECY_HPS_SIEV_WTP	0.000000	0.000000
WASTE_DIS_WW_SWSEP	0.000000	0.000000
WASTE_DIS_WW_FILT	0.000000	0.000000
RR_WW_WTP	0.8800000	0.000000

APPENDIX D

LINGO FILES AND RESULTS OF CHAPTER 6

CHAPTER 6

INTEGRATED DESIGN OF TOTAL RESOURCE CONSERVATION NETWORKS AND INDUSTRIAL PROCESSES VIA MATERIAL FLOW COST ACCOUNTING

Coding of Case Study:

```
!MASS FLOW BALANCE, M3/DAY;

!EQUATION 1;
F_OUT_FW = F_OUT_FW2RPG + F_OUT_FW2FSEP + F_OUT_FW2SIEV;
                        F_OUT_FW = 0;
F_OUT_TRW = F_OUT_TRW2RPG + F_OUT_TRW2FSEP + F_OUT_TRW2SIEV;
F_OUT_FSEP = F_OUT_FSEP2RPG + F_OUT_FSEP2FSEP + F_OUT_FSEP2SIEV +
F_OUT_FSEP2CHEM;
      !F_OUT_FSEP2RPG = 0;
      !F_OUT_FSEP2FSEP = 0;
      !F_OUT_FSEP2SIEV = 0;
F_OUT_SIEV = F_OUT_SIEV2RPG + F_OUT_SIEV2FSEP + F_OUT_SIEV2SIEV +
F_OUT_SIEV2CHEM;
      !F_OUT_SIEV2RPG = 0;
      !F_OUT_SIEV2FSEP = 0;
      !F_OUT_SIEV2SIEV = 0;
F_OUT_SWSEP = F_OUT_SWSEP2RPG + F_OUT_SWSEP2FSEP + F_OUT_SWSEP2SIEV
+ F_OUT_SWSEP2CHEM;
      !F_OUT_SWSEP2RPG = 0;
      !F_OUT_SWSEP2FSEP = 0;
      !F_OUT_SWSEP2SIEV = 0;
F_OUT_FILT = F_OUT_FILT2RPG + F_OUT_FILT2FSEP + F_OUT_FILT2SIEV +
F_OUT_FILT2CHEM;
      !F_OUT_FILT2RPG = 0;
      !F_OUT_FILT2FSEP = 0;
      !F_OUT_FILT2SIEV = 0;
!EQUATION 2;
F_OUT_FSEP = 79;  F_OUT_SIEV = 119.4;  F_OUT_SWSEP = 59.7;
F_OUT_FILT = 17.9;  F_OUT_FW >= 0; F_OUT_TRW >= 0;
!EQUATION 3;
F_IN_CHEM = F_OUT_FSEP2CHEM + F_OUT_SIEV2CHEM + F_OUT_SWSEP2CHEM +
F_OUT_FILT2CHEM + F_WW_SLUD2CHEM;
F_IN_BIO = F_OUT_WW_CHEM2BIO;
F_IN_TERT = F_OUT_WW_BIO2TERT;
!EQUATION 4;
F_OUT_CHEM = F_IN_CHEM;
F_OUT_BIO = F_IN_BIO;
F_OUT_TERT = F_IN_TERT;
```

```
!EQUATION 5;
F_OUT_CHEM = F_OUT_WW_CHEM + F_OUT_SLUD_CHEM;
F_OUT_BIO = F_OUT_WW_BIO + F_OUT_SLUD_BIO;
F_OUT_TERT = F_OUT_WW_TERT;
!EQUATION 6;
F_OUT_WW_CHEM = F_OUT_WW_CHEM2RPG + F_OUT_WW_CHEM2FSEP +
F_OUT_WW_CHEM2SIEV + F_OUT_WW_CHEM2BIO;
      !F_OUT_WW_CHEM2RPG = 0;
      !F_OUT_WW_CHEM2FSEP = 0;
      !F_OUT_WW_CHEM2SIEV = 0;
F_OUT_WW_BIO = F_OUT_WW_BIO2RPG + F_OUT_WW_BIO2FSEP +
F_OUT_WW_BIO2SIEV + F_OUT_WW_BIO2TERT;
      !F_OUT_WW_BIO2RPG = 0;
      !F_OUT_WW_BIO2FSEP = 0;
      !F_OUT_WW_BIO2SIEV = 0;
F_OUT_WW_TERT = F_OUT_WW_TERT2RPG + F_OUT_WW_TERT2FSEP +
F_OUT_WW_TERT2SIEV + F_OUT_WW_DIS;
      !F_OUT_WW_TERT2RPG = 0;
      !F_OUT_WW_TERT2FSEP = 0;
      !F_OUT_WW_TERT2SIEV = 0;
      !F_OUT_WW_DIS = 0;

F_SLUDGE = F_OUT_SLUD_CHEM + F_OUT_SLUD_BIO;
F_SLUDGE = F_SLUD_DIS + F_WW_SLUD2CHEM;
F_SLUD_DIS = ((F_OUT_SLUD_CHEM * CC_CHEM_SLUD) + (F_OUT_SLUD_BIO *
CC_BIO_SLUD)) / 250;

CC_CHEM_SLUD = 50; !KGSS/M3;  CC_BIO_SLUD = 8; !KGSS/M3;
      CC_TERT_SLUD = 0; !KGSS/M3;

!EQUATION 7;
F_IN_RPG = F_OUT_FW2RPG + F_OUT_TRW2RPG + F_OUT_FSEP2RPG +
F_OUT_SIEV2RPG + F_OUT_SWSEP2RPG + F_OUT_FILT2RPG +
F_OUT_WW_CHEM2RPG + F_OUT_WW_BIO2RPG + F_OUT_WW_TERT2RPG;
F_IN_FSEP = F_OUT_FW2FSEP + F_OUT_TRW2FSEP + F_OUT_FSEP2FSEP +
F_OUT_SIEV2FSEP + F_OUT_SWSEP2FSEP + F_OUT_FILT2FSEP +
F_OUT_WW_CHEM2FSEP + F_OUT_WW_BIO2FSEP + F_OUT_WW_TERT2FSEP;
F_IN_SIEV = F_OUT_FW2SIEV + F_OUT_TRW2SIEV + F_OUT_FSEP2SIEV +
F_OUT_SIEV2SIEV + F_OUT_SWSEP2SIEV + F_OUT_FILT2SIEV +
F_OUT_WW_CHEM2SIEV + F_OUT_WW_BIO2SIEV + F_OUT_WW_TERT2SIEV;
! EQUATION 8;
F_IN_RPG = 36;  F_IN_FSEP = 87;  F_IN_SIEV = 120;


! CONCENTRATION BALANCE,PPM @ G/M3;

! DATA, PPM @ G/M3;
CC_OUT_FSEP_COD = 11650;      CC_OUT_FSEP_BOD = 5750;
      CC_OUT_FSEP_N = 110;    CC_OUT_FSEP_TDS = 8250;
      CC_OUT_FSEP_TSS = 4800;
CC_OUT_SIEV_COD = 4630;       CC_OUT_SIEV_BOD = 2280;
      CC_OUT_SIEV_N = 45;     CC_OUT_SIEV_TDS = 3270;
      CC_OUT_SIEV_TSS = 1900;
CC_OUT_SWSEP_COD = 8410;      CC_OUT_SWSEP_BOD = 2530;
      CC_OUT_SWSEP_N = 45;    CC_OUT_SWSEP_TDS = 3270;
      CC_OUT_SWSEP_TSS = 9520;
CC_OUT_FILT_COD = 9350;       CC_OUT_FILT_BOD = 2800;
      CC_OUT_FILT_N = 50;     CC_OUT_FILT_TDS = 3640;
      CC_OUT_FILT_TSS = 10580;
```

```
CC_OUT_WW_SLUD_COD = 2460;     CC_OUT_WW_SLUD_BOD = 1220;
      CC_OUT_WW_SLUD_N = 60;         CC_OUT_WW_SLUD_TDS = 130;
      CC_OUT_WW_SLUD_TSS = 130;

EFF_CHEM_COD = 0.65;           EFF_CHEM_BOD = 0.60;
      EFF_CHEM_N = 0.1;        EFF_CHEM_TDS = 0.98;
      EFF_CHEM_TSS = 0.98;
EFF_BIO_COD = 0.95;            EFF_BIO_BOD = 0.95;
      EFF_BIO_N = 0.8;         EFF_BIO_TDS = 0.35;
      EFF_BIO_TSS = 0.35;
EFF_TERT_COD = 0.60;           EFF_TERT_BOD = 0.60;
      EFF_TERT_N = 0;          EFF_TERT_TDS = 0.10;
      EFF_TERT_TSS = 0.10;

CC_CHEM_SLUD = 50; !KGSS/M3;  CC_BIO_SLUD = 8; !KGSS/M3;
      CC_TERT_SLUD = 0; !KGSS/M3;

S_CHEM_SLUD_COD = 0;           S_CHEM_SLUD_BOD = 0;
      S_CHEM_SLUD_N = 0;       S_CHEM_SLUD_TDS = 1;
      S_CHEM_SLUD_TSS = 1;
S_BIO_SLUD_COD = 0.35;         S_BIO_SLUD_BOD = 0;
      S_BIO_SLUD_N = 0;        S_BIO_SLUD_TDS = 1;
      S_BIO_SLUD_TSS = 1;
S_TERT_SLUD_COD = 0;           S_TERT_SLUD_BOD = 0;
      S_TERT_SLUD_N = 0;       S_TERT_SLUD_TDS = 0;
      S_TERT_SLUD_TSS = 0;

DOSE_CHEM_COAG = 500;          DOSE_CHEM_POLY = 5;
      DOSE_CHEM_NAOH = 300;
DOSE_BIO_COAG = 0;             DOSE_BIO_POLY = 0;
      DOSE_BIO_NAOH = 0;
DOSE_TERT_COAG = 0;            DOSE_TERT_POLY = 0;
      DOSE_TERT_NAOH = 0;

S_SLUD_COAG = 0.1;             S_SLUD_POLY = 1;
      S_SLUD_NAOH = 0;

!EQUATION SET 1, CHEM;
! EQ 1;
! COD; (F_IN_CHEM * CC_IN_CHEM_COD) = (F_OUT_FSEP2CHEM *
CC_OUT_FSEP_COD) + (F_OUT_SIEV2CHEM * CC_OUT_SIEV_COD) +
(F_OUT_SWSEP2CHEM * CC_OUT_SWSEP_COD)
                                    + (F_OUT_FILT2CHEM *
CC_OUT_FILT_COD) + (F_WW_SLUD2CHEM * CC_OUT_WW_SLUD_COD);
! BOD; (F_IN_CHEM * CC_IN_CHEM_BOD) = (F_OUT_FSEP2CHEM *
CC_OUT_FSEP_BOD) + (F_OUT_SIEV2CHEM * CC_OUT_SIEV_BOD) +
(F_OUT_SWSEP2CHEM * CC_OUT_SWSEP_BOD)
                                    + (F_OUT_FILT2CHEM *
CC_OUT_FILT_BOD) + (F_WW_SLUD2CHEM * CC_OUT_WW_SLUD_BOD);
! N;   (F_IN_CHEM * CC_IN_CHEM_N)   = (F_OUT_FSEP2CHEM *
CC_OUT_FSEP_N) + (F_OUT_SIEV2CHEM * CC_OUT_SIEV_N) +
(F_OUT_SWSEP2CHEM * CC_OUT_SWSEP_N)
                                    + (F_OUT_FILT2CHEM *
CC_OUT_FILT_N) + (F_WW_SLUD2CHEM * CC_OUT_WW_SLUD_N);
! TDS; (F_IN_CHEM * CC_IN_CHEM_TDS) = (F_OUT_FSEP2CHEM *
CC_OUT_FSEP_TDS) + (F_OUT_SIEV2CHEM * CC_OUT_SIEV_TDS) +
(F_OUT_SWSEP2CHEM * CC_OUT_SWSEP_TDS)
                                    + (F_OUT_FILT2CHEM *
CC_OUT_FILT_TDS) + (F_WW_SLUD2CHEM * CC_OUT_WW_SLUD_TDS);
```

```
! TSS; (F_IN_CHEM * CC_IN_CHEM_TSS) = (F_OUT_FSEP2CHEM *
CC_OUT_FSEP_TSS) + (F_OUT_SIEV2CHEM * CC_OUT_SIEV_TSS) +
(F_OUT_SWSEP2CHEM * CC_OUT_SWSEP_TSS)
                                    + (F_OUT_FILT2CHEM *
CC_OUT_FILT_TSS) + (F_WW_SLUD2CHEM * CC_OUT_WW_SLUD_TSS);
! EQ 2;
F_OUT_SLUD_CHEM * CC_CHEM_SLUD = (F_IN_CHEM * CC_IN_CHEM_COD *
EFF_CHEM_COD * S_CHEM_SLUD_COD / 1000) +
                                 (F_IN_CHEM * CC_IN_CHEM_BOD *
EFF_CHEM_BOD * S_CHEM_SLUD_BOD / 1000) +
                                 (F_IN_CHEM * CC_IN_CHEM_N *
EFF_CHEM_N * S_CHEM_SLUD_N / 1000) +
                                 (F_IN_CHEM * CC_IN_CHEM_TDS *
EFF_CHEM_TDS * S_CHEM_SLUD_TDS / 1000) +
                                 (F_IN_CHEM * CC_IN_CHEM_TSS *
EFF_CHEM_TSS * S_CHEM_SLUD_TSS / 1000) +
                                    (F_IN_CHEM * DOSE_CHEM_COAG *
S_SLUD_COAG / 1000) +
                                    (F_IN_CHEM * DOSE_CHEM_POLY *
S_SLUD_POLY / 1000) +
                                    (F_IN_CHEM * DOSE_CHEM_NAOH *
S_SLUD_NAOH / 1000) ;

! EQ 3;
(F_OUT_WW_CHEM * CC_OUT_CHEM_COD) = (F_IN_CHEM * CC_IN_CHEM_COD) *
(1 - EFF_CHEM_COD);
(F_OUT_WW_CHEM * CC_OUT_CHEM_BOD) = (F_IN_CHEM * CC_IN_CHEM_BOD) *
(1 - EFF_CHEM_BOD);
(F_OUT_WW_CHEM * CC_OUT_CHEM_N) = (F_IN_CHEM * CC_IN_CHEM_N) * (1 -
EFF_CHEM_N);
(F_OUT_WW_CHEM * CC_OUT_CHEM_TDS) = (F_IN_CHEM * CC_IN_CHEM_TDS) *
(1 - EFF_CHEM_TDS);
(F_OUT_WW_CHEM * CC_OUT_CHEM_TSS) = (F_IN_CHEM * CC_IN_CHEM_TSS) *
(1 - EFF_CHEM_TSS);

!EQUATION SET 1, BIO;
! EQ 1;
! COD; (F_IN_BIO * CC_IN_BIO_COD) = (F_OUT_WW_CHEM2BIO *
CC_OUT_CHEM_COD);
! BOD; (F_IN_BIO * CC_IN_BIO_BOD) = (F_OUT_WW_CHEM2BIO *
CC_OUT_CHEM_BOD);
! N;   (F_IN_BIO * CC_IN_BIO_N) = (F_OUT_WW_CHEM2BIO *
CC_OUT_CHEM_N);
! TDS; (F_IN_BIO * CC_IN_BIO_TDS) = (F_OUT_WW_CHEM2BIO *
CC_OUT_CHEM_TDS);
! TSS; (F_IN_BIO * CC_IN_BIO_TSS) = (F_OUT_WW_CHEM2BIO *
CC_OUT_CHEM_TSS);

! EQ 2;
F_OUT_SLUD_BIO * CC_BIO_SLUD = (F_IN_BIO * CC_IN_BIO_COD *
EFF_BIO_COD * S_BIO_SLUD_COD / 1000) +
                                 (F_IN_BIO * CC_IN_BIO_BOD *
EFF_BIO_BOD * S_BIO_SLUD_BOD / 1000) +
                                 (F_IN_BIO * CC_IN_BIO_N * EFF_BIO_N
* S_BIO_SLUD_N / 1000) +
                                 (F_IN_BIO * CC_IN_BIO_TDS *
EFF_BIO_TDS * S_BIO_SLUD_TDS / 1000) +
                                 (F_IN_BIO * CC_IN_BIO_TSS *
EFF_BIO_TSS * S_BIO_SLUD_TSS / 1000) +
```

```
                                    (F_IN_BIO * DOSE_BIO_COAG *
S_SLUD_COAG / 1000) +
                                    (F_IN_BIO * DOSE_BIO_POLY *
S_SLUD_POLY / 1000) +
                                    (F_IN_BIO * DOSE_BIO_NAOH *
S_SLUD_NAOH / 1000) ;

! EQ 3;
(F_OUT_WW_BIO * CC_OUT_BIO_COD) = (F_IN_BIO * CC_IN_BIO_COD) * (1 -
EFF_BIO_COD);
(F_OUT_WW_BIO * CC_OUT_BIO_BOD) = (F_IN_BIO * CC_IN_BIO_BOD) * (1 -
EFF_BIO_BOD);
(F_OUT_WW_BIO * CC_OUT_BIO_N) = (F_IN_BIO * CC_IN_BIO_N) * (1 -
EFF_BIO_N);
(F_OUT_WW_BIO * CC_OUT_BIO_TDS) = (F_IN_BIO * CC_IN_BIO_TDS) * (1 -
EFF_BIO_TDS);
(F_OUT_WW_BIO * CC_OUT_BIO_TSS) = (F_IN_BIO * CC_IN_BIO_TSS) * (1 -
EFF_BIO_TSS);

!EQUATION SET 1, TERT;
! EQ 1;
! COD; (F_IN_TERT * CC_IN_TERT_COD) = (F_OUT_WW_BIO2TERT *
CC_OUT_BIO_COD);
! BOD; (F_IN_TERT * CC_IN_TERT_BOD) = (F_OUT_WW_BIO2TERT *
CC_OUT_BIO_BOD);
! N;   (F_IN_TERT * CC_IN_TERT_N) = (F_OUT_WW_BIO2TERT *
CC_OUT_BIO_N);
! TDS; (F_IN_TERT * CC_IN_TERT_TDS) = (F_OUT_WW_BIO2TERT *
CC_OUT_BIO_TDS);
! TSS; (F_IN_TERT * CC_IN_TERT_TSS) = (F_OUT_WW_BIO2TERT *
CC_OUT_BIO_TSS);

! EQ 2; ! TERT HAVE NO SLUDGE GENERATION;

! EQ 3;
(F_OUT_WW_TERT * CC_OUT_TERT_COD) = (F_IN_TERT * CC_IN_TERT_COD) *
(1 - EFF_TERT_COD);
(F_OUT_WW_TERT * CC_OUT_TERT_BOD) = (F_IN_TERT * CC_IN_TERT_BOD) *
(1 - EFF_TERT_BOD);
(F_OUT_WW_TERT * CC_OUT_TERT_N) = (F_IN_TERT * CC_IN_TERT_N) * (1 -
EFF_TERT_N);
(F_OUT_WW_TERT * CC_OUT_TERT_TDS) = (F_IN_TERT * CC_IN_TERT_TDS) *
(1 - EFF_TERT_TDS);
(F_OUT_WW_TERT * CC_OUT_TERT_TSS) = (F_IN_TERT * CC_IN_TERT_TSS) *
(1 - EFF_TERT_TSS);

! DATA, PPM @ G/M3;
CC_OUT_FW_COD = 10;     CC_OUT_FW_BOD = 6;      CC_OUT_FW_N = 1;
      CC_OUT_FW_TDS = 10;     CC_OUT_FW_TSS = 10;
CC_OUT_TRW_COD = 150;   CC_OUT_TRW_BOD = 100;   CC_OUT_TRW_N = 10;
      CC_OUT_TRW_TDS = 100;   CC_OUT_TRW_TSS = 100;

CC_OUT_FSEP_COD = 11650;      CC_OUT_FSEP_BOD = 5750;
      CC_OUT_FSEP_N = 110;    CC_OUT_FSEP_TDS = 8250;
      CC_OUT_FSEP_TSS = 4800;
CC_OUT_SIEV_COD = 4630;       CC_OUT_SIEV_BOD = 2280;
      CC_OUT_SIEV_N = 45;     CC_OUT_SIEV_TDS = 3270;
      CC_OUT_SIEV_TSS = 1900;
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CC_OUT_SWSEP_COD = 8410;      CC_OUT_SWSEP_BOD = 2530;
      CC_OUT_SWSEP_N = 45;    CC_OUT_SWSEP_TDS = 3270;
      CC_OUT_SWSEP_TSS = 9520;
CC_OUT_FILT_COD = 9350;       CC_OUT_FILT_BOD = 2800;
      CC_OUT_FILT_N = 50;     CC_OUT_FILT_TDS = 3640;
      CC_OUT_FILT_TSS = 10580;

! EQUATION 4;
! RPG;
! COD; (F_IN_RPG * CC_IN_RPG_COD) = (F_OUT_FW2RPG * CC_OUT_FW_COD) +
(F_OUT_TRW2RPG * CC_OUT_TRW_COD) + (F_OUT_FSEP2RPG * CC_OUT_FSEP_COD)
                                  + (F_OUT_SIEV2RPG *
CC_OUT_SIEV_COD) + (F_OUT_SWSEP2RPG * CC_OUT_SWSEP_COD) +
(F_OUT_FILT2RPG * CC_OUT_FILT_COD)
                                  + (F_OUT_WW_CHEM2RPG *
CC_OUT_CHEM_COD) + (F_OUT_WW_BIO2RPG * CC_OUT_BIO_COD) +
(F_OUT_WW_TERT2RPG * CC_OUT_TERT_COD);
! BOD; (F_IN_RPG * CC_IN_RPG_BOD) = (F_OUT_FW2RPG * CC_OUT_FW_BOD) +
(F_OUT_TRW2RPG * CC_OUT_TRW_BOD) + (F_OUT_FSEP2RPG * CC_OUT_FSEP_BOD)
                                  + (F_OUT_SIEV2RPG *
CC_OUT_SIEV_BOD) + (F_OUT_SWSEP2RPG * CC_OUT_SWSEP_BOD) +
(F_OUT_FILT2RPG * CC_OUT_FILT_BOD)
                                  + (F_OUT_WW_CHEM2RPG *
CC_OUT_CHEM_BOD) + (F_OUT_WW_BIO2RPG * CC_OUT_BIO_BOD) +
(F_OUT_WW_TERT2RPG * CC_OUT_TERT_BOD);
! N; (F_IN_RPG * CC_IN_RPG_N) = (F_OUT_FW2RPG * CC_OUT_FW_N) +
(F_OUT_TRW2RPG * CC_OUT_TRW_N) + (F_OUT_FSEP2RPG * CC_OUT_FSEP_N)
                              + (F_OUT_SIEV2RPG * CC_OUT_SIEV_N) +
(F_OUT_SWSEP2RPG * CC_OUT_SWSEP_N) + (F_OUT_FILT2RPG * CC_OUT_FILT_N)
                              + (F_OUT_WW_CHEM2RPG * CC_OUT_CHEM_N)
+ (F_OUT_WW_BIO2RPG * CC_OUT_BIO_N) + (F_OUT_WW_TERT2RPG *
CC_OUT_TERT_N);
! TDS; (F_IN_RPG * CC_IN_RPG_TDS) = (F_OUT_FW2RPG * CC_OUT_FW_TDS) +
(F_OUT_TRW2RPG * CC_OUT_TRW_TDS) + (F_OUT_FSEP2RPG * CC_OUT_FSEP_TDS)
                                  + (F_OUT_SIEV2RPG *
CC_OUT_SIEV_TDS) + (F_OUT_SWSEP2RPG * CC_OUT_SWSEP_TDS) +
(F_OUT_FILT2RPG * CC_OUT_FILT_TDS)
                                  + (F_OUT_WW_CHEM2RPG *
CC_OUT_CHEM_TDS) + (F_OUT_WW_BIO2RPG * CC_OUT_BIO_TDS) +
(F_OUT_WW_TERT2RPG * CC_OUT_TERT_TDS);
! TSS; (F_IN_RPG * CC_IN_RPG_TSS) = (F_OUT_FW2RPG * CC_OUT_FW_TSS) +
(F_OUT_TRW2RPG * CC_OUT_TRW_TSS) + (F_OUT_FSEP2RPG * CC_OUT_FSEP_TSS)
                                  + (F_OUT_SIEV2RPG *
CC_OUT_SIEV_TSS) + (F_OUT_SWSEP2RPG * CC_OUT_SWSEP_TSS) +
(F_OUT_FILT2RPG * CC_OUT_FILT_TSS)
                                  + (F_OUT_WW_CHEM2RPG *
CC_OUT_CHEM_TSS) + (F_OUT_WW_BIO2RPG * CC_OUT_BIO_TSS) +
(F_OUT_WW_TERT2RPG * CC_OUT_TERT_TSS);

! FSEP;
! COD; (F_IN_FSEP * CC_IN_FSEP_COD) = (F_OUT_FW2FSEP * CC_OUT_FW_COD)
+ (F_OUT_TRW2FSEP * CC_OUT_TRW_COD) + (F_OUT_FSEP2FSEP *
CC_OUT_FSEP_COD)
                                  + (F_OUT_SIEV2FSEP *
CC_OUT_SIEV_COD) + (F_OUT_SWSEP2FSEP * CC_OUT_SWSEP_COD) +
(F_OUT_FILT2FSEP * CC_OUT_FILT_COD)
                                  + (F_OUT_WW_CHEM2FSEP *
CC_OUT_CHEM_COD) + (F_OUT_WW_BIO2FSEP * CC_OUT_BIO_COD) +
(F_OUT_WW_TERT2FSEP * CC_OUT_TERT_COD);
```

```
! BOD; (F_IN_FSEP * CC_IN_FSEP_BOD) = (F_OUT_FW2FSEP * CC_OUT_FW_BOD)
+ (F_OUT_TRW2FSEP * CC_OUT_TRW_BOD) + (F_OUT_FSEP2FSEP *
CC_OUT_FSEP_BOD)
                                    + (F_OUT_SIEV2FSEP *
CC_OUT_SIEV_BOD) + (F_OUT_SWSEP2FSEP * CC_OUT_SWSEP_BOD) +
(F_OUT_FILT2FSEP * CC_OUT_FILT_BOD)
                                    + (F_OUT_WW_CHEM2FSEP *
CC_OUT_CHEM_BOD) + (F_OUT_WW_BIO2FSEP * CC_OUT_BIO_BOD) +
(F_OUT_WW_TERT2FSEP * CC_OUT_TERT_BOD);
! N; (F_IN_FSEP * CC_IN_FSEP_N) = (F_OUT_FW2FSEP * CC_OUT_FW_N) +
(F_OUT_TRW2FSEP * CC_OUT_TRW_N) + (F_OUT_FSEP2FSEP * CC_OUT_FSEP_N)
                                + (F_OUT_SIEV2FSEP * CC_OUT_SIEV_N) +
(F_OUT_SWSEP2FSEP * CC_OUT_SWSEP_N) + (F_OUT_FILT2FSEP *
CC_OUT_FILT_N)
                                + (F_OUT_WW_CHEM2FSEP * CC_OUT_CHEM_N)
+ (F_OUT_WW_BIO2FSEP * CC_OUT_BIO_N) + (F_OUT_WW_TERT2FSEP *
CC_OUT_TERT_N);
! TDS; (F_IN_FSEP * CC_IN_FSEP_TDS) = (F_OUT_FW2FSEP * CC_OUT_FW_TDS)
+ (F_OUT_TRW2FSEP * CC_OUT_TRW_TDS) + (F_OUT_FSEP2FSEP *
CC_OUT_FSEP_TDS)
                                    + (F_OUT_SIEV2FSEP *
CC_OUT_SIEV_TDS) + (F_OUT_SWSEP2FSEP * CC_OUT_SWSEP_TDS) +
(F_OUT_FILT2FSEP * CC_OUT_FILT_TDS)
                                    + (F_OUT_WW_CHEM2FSEP *
CC_OUT_CHEM_TDS) + (F_OUT_WW_BIO2FSEP * CC_OUT_BIO_TDS) +
(F_OUT_WW_TERT2FSEP * CC_OUT_TERT_TDS);
! TSS; (F_IN_FSEP * CC_IN_FSEP_TSS) = (F_OUT_FW2FSEP * CC_OUT_FW_TSS)
+ (F_OUT_TRW2FSEP * CC_OUT_TRW_TSS) + (F_OUT_FSEP2FSEP *
CC_OUT_FSEP_TSS)
                                    + (F_OUT_SIEV2FSEP *
CC_OUT_SIEV_TSS) + (F_OUT_SWSEP2FSEP * CC_OUT_SWSEP_TSS) +
(F_OUT_FILT2FSEP * CC_OUT_FILT_TSS)
                                    + (F_OUT_WW_CHEM2FSEP *
CC_OUT_CHEM_TSS) + (F_OUT_WW_BIO2FSEP * CC_OUT_BIO_TSS) +
(F_OUT_WW_TERT2FSEP * CC_OUT_TERT_TSS);

! SIEV;
! COD; (F_IN_SIEV * CC_IN_SIEV_COD) = (F_OUT_FW2SIEV * CC_OUT_FW_COD)
+ (F_OUT_TRW2SIEV * CC_OUT_TRW_COD) + (F_OUT_FSEP2SIEV *
CC_OUT_FSEP_COD)
                                    + (F_OUT_SIEV2SIEV *
CC_OUT_SIEV_COD) + (F_OUT_SWSEP2SIEV * CC_OUT_SWSEP_COD) +
(F_OUT_FILT2SIEV * CC_OUT_FILT_COD)
                                    + (F_OUT_WW_CHEM2SIEV *
CC_OUT_CHEM_COD) + (F_OUT_WW_BIO2SIEV * CC_OUT_BIO_COD) +
(F_OUT_WW_TERT2SIEV * CC_OUT_TERT_COD);
! BOD; (F_IN_SIEV * CC_IN_SIEV_BOD) = (F_OUT_FW2SIEV * CC_OUT_FW_BOD)
+ (F_OUT_TRW2SIEV * CC_OUT_TRW_BOD) + (F_OUT_FSEP2SIEV *
CC_OUT_FSEP_BOD)
                                    + (F_OUT_SIEV2SIEV *
CC_OUT_SIEV_BOD) + (F_OUT_SWSEP2SIEV * CC_OUT_SWSEP_BOD) +
(F_OUT_FILT2SIEV * CC_OUT_FILT_BOD)
                                    + (F_OUT_WW_CHEM2SIEV *
CC_OUT_CHEM_BOD) + (F_OUT_WW_BIO2SIEV * CC_OUT_BIO_BOD) +
(F_OUT_WW_TERT2SIEV * CC_OUT_TERT_BOD);
! N; (F_IN_SIEV * CC_IN_SIEV_N) = (F_OUT_FW2SIEV * CC_OUT_FW_N) +
(F_OUT_TRW2SIEV * CC_OUT_TRW_N) + (F_OUT_FSEP2SIEV * CC_OUT_FSEP_N)
                                + (F_OUT_SIEV2SIEV * CC_OUT_SIEV_N) +
(F_OUT_SWSEP2SIEV * CC_OUT_SWSEP_N) + (F_OUT_FILT2SIEV *
CC_OUT_FILT_N)
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                              + (F_OUT_WW_CHEM2SIEV * CC_OUT_CHEM_N)
+ (F_OUT_WW_BIO2SIEV * CC_OUT_BIO_N) + (F_OUT_WW_TERT2SIEV *
CC_OUT_TERT_N);
! TDS; (F_IN_SIEV * CC_IN_SIEV_TDS) = (F_OUT_FW2SIEV * CC_OUT_FW_TDS)
+ (F_OUT_TRW2SIEV * CC_OUT_TRW_TDS) + (F_OUT_FSEP2SIEV *
CC_OUT_FSEP_TDS)
                                  + (F_OUT_SIEV2SIEV *
CC_OUT_SIEV_TDS) + (F_OUT_SWSEP2SIEV * CC_OUT_SWSEP_TDS) +
(F_OUT_FILT2SIEV * CC_OUT_FILT_TDS)
                                  + (F_OUT_WW_CHEM2SIEV *
CC_OUT_CHEM_TDS) + (F_OUT_WW_BIO2SIEV * CC_OUT_BIO_TDS) +
(F_OUT_WW_TERT2SIEV * CC_OUT_TERT_TDS);
! TSS; (F_IN_SIEV * CC_IN_SIEV_TSS) = (F_OUT_FW2SIEV * CC_OUT_FW_TSS)
+ (F_OUT_TRW2SIEV * CC_OUT_TRW_TSS) + (F_OUT_FSEP2SIEV *
CC_OUT_FSEP_TSS)
                                  + (F_OUT_SIEV2SIEV *
CC_OUT_SIEV_TSS) + (F_OUT_SWSEP2SIEV * CC_OUT_SWSEP_TSS) +
(F_OUT_FILT2SIEV * CC_OUT_FILT_TSS)
                                  + (F_OUT_WW_CHEM2SIEV *
CC_OUT_CHEM_TSS) + (F_OUT_WW_BIO2SIEV * CC_OUT_BIO_TSS) +
(F_OUT_WW_TERT2SIEV * CC_OUT_TERT_TSS);

! EQUATION 5;
CC_IN_RPG_COD <= 300;   CC_IN_RPG_BOD <= 150;    CC_IN_RPG_N <= 20;
CC_IN_RPG_TDS <= 150;    CC_IN_RPG_TSS <= 150;
CC_IN_FSEP_COD <= 300;  CC_IN_FSEP_BOD <= 150;   CC_IN_FSEP_N <= 20;
CC_IN_FSEP_TDS <= 150;   CC_IN_FSEP_TSS <= 150;
CC_IN_SIEV_COD <= 300;  CC_IN_SIEV_BOD <= 150;   CC_IN_SIEV_N <= 20;
CC_IN_SIEV_TDS <= 150;   CC_IN_SIEV_TSS <= 150;

! EUQATION 6;
CC_OUT_TERT_COD <= 200;
CC_OUT_TERT_BOD <= 50;
CC_OUT_TERT_N <= 20;
CC_OUT_TERT_TDS <= 100;
CC_OUT_TERT_TSS <= 100;

!MIN = F_OUT_WW_DIS;
!MIN = F_OUT_FW;
!MIN = F_SLUDGE;


! COST COMPUTATION, USD;
! WTP;
HC_WTP = PC_WTP + CFC_WTP;                             PC_WTP = 20.1;
      CFC_WTP = 0;
HUC_WTP = HC_WTP/F_OUT_TRW;
CFC_INT_WTP2RPG = HUC_WTP * F_OUT_TRW2RPG;
CFC_INT_WTP2FSEP = HUC_WTP * F_OUT_TRW2FSEP;
CFC_INT_WTP2SIEV = HUC_WTP * F_OUT_TRW2SIEV;
! DBK;
HC_DBK = PC_DBK + CFC_DBK;                             PC_DBK =
2355.8;     CFC_DBK = 0;
HUC_DBK = HC_DBK / TOT_OUT_DBK;                        TOT_OUT_DBK =
83.2;
CFC_INT_DBK2RPG = HUC_DBK * INT_DBK2RPG;               INT_DBK2RPG =
62.4;
HC_Y_DBK = HUC_DBK * DIS_DBK;                         DIS_DBK = 20.8;
! RPG;
HC_RPG = PC_RPG + CFC_RPG;                             PC_RPG = 97.0;
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CFC_RPG = CFC_INT_DBK2RPG + CFC_FW2RPG + CFC_INT_WTP2PRG +
CFC_FSEP2RPG + CFC_SIEV2RPG + CFC_SWSEP2RPG + CFC_FILT2RPG +
CFC_WW_CHEM2RPG + CFC_WW_BIO2RPG + CFC_WW_TERT2RPG;
CFC_FW2RPG = HUC_FW * F_OUT_FW2RPG;                   HUC_FW =
0.33; !USD 0.33/M3;
CFC_INT_WTP2PRG = HUC_WTP * F_OUT_TRW2RPG;
CFC_FSEP2RPG = HUC_FSEP * F_OUT_FSEP2RPG;
CFC_SIEV2RPG = HUC_SIEV * F_OUT_SIEV2RPG;
CFC_SWSEP2RPG = HUC_SWSEP * F_OUT_SWSEP2RPG;
CFC_FILT2RPG = HUC_FILT * F_OUT_FILT2RPG;
CFC_WW_CHEM2RPG = HUC_CHEM * F_OUT_WW_CHEM2RPG;
CFC_WW_BIO2RPG = HUC_BIO * F_OUT_WW_BIO2RPG;
CFC_WW_TERT2RPG = HUC_TERT * F_OUT_WW_TERT2RPG;
HUC_RPG = HC_RPG / TOT_OUT_RPG;                       TOT_OUT_RPG =
98.4;
CFC_INT_RPG2FSEP = HUC_RPG * INT_RPG2FSEP;            INT_RPG2FSEP =
98.4;
! FSEP;
HC_FSEP = PC_FSEP + CFC_FSEP;                        PC_FSEP = 56.4;
CFC_FSEP = CFC_INT_RPG2FSEP + CFC_FW2FSEP + CFC_INT_WTP2FSEP +
CFC_FSEP2FSEP + CFC_SIEV2FSEP + CFC_SWSEP2FSEP + CFC_FILT2FSEP +
CFC_WW_CHEM2FSEP + CFC_WW_BIO2FSEP + CFC_WW_TERT2FSEP;
CFC_FW2FSEP = HUC_FW * F_OUT_FW2FSEP;                 HUC_FW =
0.33; !USD 0.33/M3;
CFC_INT_WTP2FSEP = HUC_WTP * F_OUT_TRW2FSEP;
CFC_FSEP2FSEP = HUC_FSEP * F_OUT_FSEP2FSEP;
CFC_SIEV2FSEP = HUC_SIEV * F_OUT_SIEV2FSEP;
CFC_SWSEP2FSEP = HUC_SWSEP * F_OUT_SWSEP2FSEP;
CFC_FILT2FSEP = HUC_FILT * F_OUT_FILT2FSEP;
CFC_WW_CHEM2FSEP = HUC_CHEM * F_OUT_WW_CHEM2FSEP;
CFC_WW_BIO2FSEP = HUC_BIO * F_OUT_WW_BIO2FSEP;
CFC_WW_TERT2FSEP = HUC_TERT * F_OUT_WW_TERT2FSEP;
HUC_FSEP = HC_FSEP / TOT_OUT_FSEP;                    TOT_OUT_FSEP =
185.4;
CFC_INT_FSEP2SIEV = HUC_FSEP * INT_FSEP2SIEV;         INT_FSEP2SIEV
= 91.3;
CFC_INT_FSEP2CHEM = HUC_FSEP * F_OUT_FSEP2CHEM;
HC_Y_FSEP = HUC_FSEP * DIS_FSEP;                      DIS_FSEP =
15.1;
! SIEV;
HC_SIEV = PC_SIEV + CFC_SIEV;                        PC_SIEV = 40.5;
CFC_SIEV = CFC_INT_FSEP2SIEV + CFC_FW2SIEV + CFC_INT_WTP2SIEV +
CFC_FSEP2SIEV + CFC_SIEV2SIEV + CFC_SWSEP2SIEV + CFC_FILT2SIEV +
CFC_WW_CHEM2SIEV + CFC_WW_BIO2SIEV + CFC_WW_TERT2SIEV;
CFC_FW2SIEV = HUC_FW * F_OUT_FW2SIEV;                 HUC_FW =
0.33; !USD 0.33/M3;
CFC_INT_WTP2SIEV = HUC_WTP * F_OUT_TRW2SIEV;
CFC_FSEP2SIEV = HUC_FSEP * F_OUT_FSEP2SIEV;
CFC_SIEV2SIEV = HUC_SIEV * F_OUT_SIEV2SIEV;
CFC_SWSEP2SIEV = HUC_SWSEP * F_OUT_SWSEP2SIEV;
CFC_FILT2SIEV = HUC_FILT * F_OUT_FILT2SIEV;
CFC_WW_CHEM2SIEV = HUC_CHEM * F_OUT_WW_CHEM2SIEV;
CFC_WW_BIO2SIEV = HUC_BIO * F_OUT_WW_BIO2SIEV;
CFC_WW_TERT2SIEV = HUC_TERT * F_OUT_WW_TERT2SIEV;
HUC_SIEV = HC_SIEV / TOT_OUT_SIEV;                    TOT_OUT_SIEV =
211.3;
CFC_INT_SIEV2SWSEP = HUC_SIEV * INT_SIEV2SWSEP;       INT_SIEV2SWSEP
= 90.1;
CFC_INT_SIEV2CHEM = HUC_SIEV * F_OUT_SIEV2CHEM;
HC_Y_SIEV = HUC_SIEV * DIS_SIEV;                     DIS_SIEV = 1.8;
```

```
! SWSEP;
HC_SWSEP = PC_SWSEP + CFC_SWSEP;                              PC_SWSEP =
44.3;
CFC_SWSEP = CFC_INT_SIEV2SWSEP;
HUC_SWSEP = HC_SWSEP / TOT_OUT_SWSEP;                         TOT_OUT_SWSEP
= 90.1;
CFC_INT_SWSEP2FILT = HUC_SWSEP * INT_SWSEP2FILT;              INT_SWSEP2FILT
= 30.4;
CFC_INT_SWSEP2CHEM = HUC_SWSEP * F_OUT_SWSEP2CHEM;
! FILT;
HC_FILT = PC_FILT + CFC_FILT;                                PC_FILT = 14.1;

CFC_FILT = CFC_INT_SWSEP2FILT;
HUC_FILT = HC_FILT / TOT_OUT_FILT;                            TOT_OUT_FILT =
30.4;
CFC_INT_FILT2DP = HUC_FILT * INT_FILT2DP;                     INT_FILT2DP =
12.5;
CFC_INT_FILT2CHEM = HUC_FILT * F_OUT_FILT2CHEM;
! DP;
HC_DP = PC_DP + CFC_DP;                                       PC_DP = 51.5;
CFC_DP = CFC_INT_FILT2DP;
HUC_DP = HC_DP / TOT_OUT_DP;                                  TOT_OUT_DP =
12.0;
HC_P_DP = HUC_DP * P_DP;                                      P_DP = 12.0;
! CHEM;
HC_CHEM = PC_CHEM + CFC_CHEM;
PC_CHEM = (261*0.11) + (0.5 * 8) + (F_IN_CHEM * DOSE_CHEM_COAG /
1000 * 0.83) + (F_IN_CHEM * DOSE_CHEM_NAOH / 1000 * 0.27) +
(F_IN_CHEM * DOSE_CHEM_POLY / 1000 * 8.33);
CFC_CHEM = CFC_INT_FSEP2CHEM + CFC_INT_SIEV2CHEM +
CFC_INT_SWSEP2CHEM + CFC_INT_FILT2CHEM + CFC_WW_SLUD2CHEM;
HUC_CHEM = HC_CHEM / F_OUT_CHEM;
CFC_WW_CHEM2RPG = HUC_CHEM * F_OUT_WW_CHEM2RPG;
CFC_WW_CHEM2FSEP = HUC_CHEM * F_OUT_WW_CHEM2FSEP;
CFC_WW_CHEM2SIEV = HUC_CHEM * F_OUT_WW_CHEM2SIEV;
CFC_SLUD_CHEM2SLUD = HUC_CHEM * F_OUT_SLUD_CHEM;
CFC_WW_CHEM2BIO = HUC_CHEM * F_OUT_WW_CHEM2BIO;
! BIO;
HC_BIO = PC_BIO + CFC_BIO;
PC_BIO = (922 * 0.11) + (0.5 * 8);
CFC_BIO = CFC_WW_CHEM2BIO;
HUC_BIO = HC_BIO / F_OUT_BIO;
CFC_WW_BIO2RPG = HUC_BIO * F_OUT_WW_BIO2RPG;
CFC_WW_BIO2FSEP = HUC_BIO * F_OUT_WW_BIO2FSEP;
CFC_WW_BIO2SIEV = HUC_BIO * F_OUT_WW_BIO2SIEV;
CFC_SLUD_BIO2SLUD = HUC_BIO * F_OUT_SLUD_BIO;
CFC_WW_BIO2TERT = HUC_BIO * F_OUT_WW_BIO2TERT;
! TERT;
HC_TERT = PC_TERT + CFC_TERT;
PC_TERT = (66 * 0.11) + (0.5 * 8) + (F_IN_TERT * CC_IN_TERT_COD *
EFF_TERT_COD / 1000 * 5 * 2.5);      ! 5 KGCORBON REQUIRED / KG COD
REMOVED @ USD 2.5 / KG CARBON;
CFC_TERT = CFC_WW_BIO2TERT;
HUC_TERT = HC_TERT / F_OUT_TERT;
CFC_WW_TERT2RPG = HUC_TERT * F_OUT_WW_TERT2RPG;
CFC_WW_TERT2FSEP = HUC_TERT * F_OUT_WW_TERT2FSEP;
CFC_WW_TERT2SIEV = HUC_TERT * F_OUT_WW_TERT2SIEV;
CFC_WW_TERT2DIS = HUC_TERT * F_OUT_WW_DIS;
HC_Y_TERT = CFC_WW_TERT2DIS;
! SLUD;
```

```
HC_SLUD = PC_SLUD + CFC_SLUD;
PC_SLUD = (29 * 0.11) + (0.5 * 8) + (((F_OUT_SLUD_CHEM *
CC_CHEM_SLUD) + (F_OUT_SLUD_BIO * CC_BIO_SLUD)) / 1000 * 6 * 8.33);
CFC_SLUD = CFC_SLUD_CHEM2SLUD + CFC_SLUD_BIO2SLUD;
HUC_SLUD = HC_SLUD / F_SLUDGE;
CFC_SLUD_DIS = HUC_SLUD * F_SLUD_DIS;
CFC_WW_SLUD2CHEM = HUC_SLUD * F_WW_SLUD2CHEM;
HC_Y_SLUD = CFC_SLUD_DIS;
! WASTE MANAGEMENT COST;
COST_WASTE_MANAGEMENT = (((F_IN_TERT * CC_IN_TERT_COD * EFF_TERT_COD
/ 1000 / 1000 * 5) * 1166.7) + (F_SLUD_DIS * 26.7)) ;
! USD 1166.7/TON (RM3500/TON) FOR KA, USD 26.7/TON (RM80/TON) FOR
LAND FILL;
THC_Y = HC_Y_DBK + HC_Y_FSEP + HC_Y_SIEV + HC_Y_TERT + HC_Y_SLUD +
COST_WASTE_MANAGEMENT;

!MIN = F_SLUD_DIS;

!1467.43 <= THC_Y;

MIN = THC_Y;

HC_Y_DBK + HC_Y_FSEP + HC_Y_SIEV + HC_P_DP + HC_Y_TERT + HC_Y_SLUD =
PC_WTP + PC_DBK + PC_RPG + PC_FSEP + PC_SIEV + PC_SWSEP + PC_FILT +
PC_DP + PC_CHEM + PC_BIO + PC_TERT + PC_SLUD;
```

Results of Case Study:

```
Global optimal solution found.
Objective value:                              2952.883
Objective bound:                              2952.883
Infeasibilities:                              0.000000
Extended solver steps:                              14
Total solver iterations:                        519766

Model Class:                                       NLP

Total variables:                    179
Nonlinear variables:                 89
Integer variables:                    0

Total constraints:                  216
Nonlinear constraints:              101

Total nonzeros:                     752
Nonlinear nonzeros:                 314
```

Variable	Value	Reduced Cost
F_OUT_FW	0.000000	0.000000
F_OUT_FW2RPG	0.000000	0.000000
F_OUT_FW2FSEP	0.000000	0.000000
F_OUT_FW2SIEV	0.000000	0.000000
F_OUT_TRW	0.1100000E-04	0.000000
F_OUT_TRW2RPG	0.000000	0.000000
F_OUT_TRW2FSEP	0.000000	0.000000
F_OUT_TRW2SIEV	0.1100000E-04	0.000000
F_OUT_FSEP	79.00000	0.000000
F_OUT_FSEP2RPG	0.000000	0.000000
F_OUT_FSEP2FSEP	0.000000	0.000000
F_OUT_FSEP2SIEV	0.000000	0.000000
F_OUT_FSEP2CHEM	79.00000	0.000000
F_OUT_SIEV	119.4000	0.000000
F_OUT_SIEV2RPG	0.7958030	0.000000
F_OUT_SIEV2FSEP	1.923191	0.000000
F_OUT_SIEV2SIEV	2.652677	0.000000
F_OUT_SIEV2CHEM	114.0283	0.000000
F_OUT_SWSEP	59.70000	0.000000
F_OUT_SWSEP2RPG	0.1569014	0.000000
F_OUT_SWSEP2FSEP	0.3791783	0.000000
F_OUT_SWSEP2SIEV	0.5230045	0.000000
F_OUT_SWSEP2CHEM	58.64092	0.000000
F_OUT_FILT	17.90000	0.000000
F_OUT_FILT2RPG	0.000000	0.000000
F_OUT_FILT2FSEP	0.000000	0.000000
F_OUT_FILT2SIEV	0.000000	0.000000
F_OUT_FILT2CHEM	17.90000	0.000000
F_IN_CHEM	345.8188	0.000000
F_WW_SLUD2CHEM	76.24957	0.000000
F_IN_BIO	292.7254	0.000000
F_OUT_WW_CHEM2BIO	292.7254	0.000000
F_IN_TERT	21.41646	0.000000
F_OUT_WW_BIO2TERT	21.41646	0.000000
F_OUT_CHEM	345.8188	0.000000
F_OUT_BIO	292.7254	0.000000
F_OUT_TERT	21.41646	0.000000

F_OUT_WW_CHEM	293.5992	0.000000
F_OUT_SLUD_CHEM	52.21959	0.000000
F_OUT_WW_BIO	257.1119	0.000000
F_OUT_SLUD_BIO	35.61353	0.000000
F_OUT_WW_TERT	21.41646	0.000000
F_OUT_WW_CHEM2RPG	0.1294574	0.000000
F_OUT_WW_CHEM2FSEP	0.3128554	0.000000
F_OUT_WW_CHEM2SIEV	0.4315249	0.000000
F_OUT_WW_BIO2RPG	34.91784	0.000000
F_OUT_WW_BIO2FSEP	84.38478	0.000000
F_OUT_WW_BIO2SIEV	116.3928	0.000000
F_OUT_WW_TERT2RPG	0.000000	0.000000
F_OUT_WW_TERT2FSEP	0.000000	0.000000
F_OUT_WW_TERT2SIEV	0.000000	0.000000
F_OUT_WW_DIS	21.41646	0.000000
F_SLUDGE	87.83312	0.000000
F_SLUD_DIS	11.58355	0.000000
CC_CHEM_SLUD	50.00000	0.000000
CC_BIO_SLUD	8.000000	0.000000
CC_TERT_SLUD	0.000000	0.000000
F_IN_RPG	36.00000	0.000000
F_IN_FSEP	87.00000	0.000000
F_IN_SIEV	120.0000	0.000000
CC_OUT_FSEP_COD	11650.00	0.000000
CC_OUT_FSEP_BOD	5750.000	0.000000
CC_OUT_FSEP_N	110.0000	0.000000
CC_OUT_FSEP_TDS	8250.000	0.000000
CC_OUT_FSEP_TSS	4800.000	0.000000
CC_OUT_SIEV_COD	4630.000	0.000000
CC_OUT_SIEV_BOD	2280.000	0.000000
CC_OUT_SIEV_N	45.00000	0.000000
CC_OUT_SIEV_TDS	3270.000	0.000000
CC_OUT_SIEV_TSS	1900.000	0.000000
CC_OUT_SWSEP_COD	8410.000	0.000000
CC_OUT_SWSEP_BOD	2530.000	0.000000
CC_OUT_SWSEP_N	45.00000	0.000000
CC_OUT_SWSEP_TDS	3270.000	0.000000
CC_OUT_SWSEP_TSS	9520.000	0.000000
CC_OUT_FILT_COD	9350.000	0.000000
CC_OUT_FILT_BOD	2800.000	0.000000
CC_OUT_FILT_N	50.00000	0.000000
CC_OUT_FILT_TDS	3640.000	0.000000
CC_OUT_FILT_TSS	10580.00	0.000000
CC_OUT_WW_SLUD_COD	2460.000	0.000000
CC_OUT_WW_SLUD_BOD	1220.000	0.000000
CC_OUT_WW_SLUD_N	60.00000	0.000000
CC_OUT_WW_SLUD_TDS	130.0000	0.000000
CC_OUT_WW_SLUD_TSS	130.0000	0.000000
EFF_CHEM_COD	0.6500000	0.000000
EFF_CHEM_BOD	0.6000000	0.000000
EFF_CHEM_N	0.1000000	0.000000
EFF_CHEM_TDS	0.9800000	0.000000
EFF_CHEM_TSS	0.9800000	0.000000
EFF_BIO_COD	0.9500000	0.000000
EFF_BIO_BOD	0.9500000	0.000000
EFF_BIO_N	0.8000000	0.000000
EFF_BIO_TDS	0.3500000	0.000000
EFF_BIO_TSS	0.3500000	0.000000
EFF_TERT_COD	0.6000000	0.000000
EFF_TERT_BOD	0.6000000	0.000000

EFF_TERT_N	0.000000	0.000000
EFF_TERT_TDS	0.1000000	0.000000
EFF_TERT_TSS	0.1000000	0.000000
S_CHEM_SLUD_COD	0.000000	0.000000
S_CHEM_SLUD_BOD	0.000000	0.000000
S_CHEM_SLUD_N	0.000000	0.000000
S_CHEM_SLUD_TDS	1.000000	0.000000
S_CHEM_SLUD_TSS	1.000000	0.000000
S_BIO_SLUD_COD	0.3500000	0.000000
S_BIO_SLUD_BOD	0.000000	0.000000
S_BIO_SLUD_N	0.000000	0.000000
S_BIO_SLUD_TDS	1.000000	0.000000
S_BIO_SLUD_TSS	1.000000	0.000000
S_TERT_SLUD_COD	0.000000	0.000000
S_TERT_SLUD_BOD	0.000000	0.000000
S_TERT_SLUD_N	0.000000	0.000000
S_TERT_SLUD_TDS	0.000000	0.000000
S_TERT_SLUD_TSS	0.000000	0.000000
DOSE_CHEM_COAG	500.0000	0.000000
DOSE_CHEM_POLY	5.000000	0.000000
DOSE_CHEM_NAOH	300.0000	0.000000
DOSE_BIO_COAG	0.000000	0.000000
DOSE_BIO_POLY	0.000000	0.000000
DOSE_BIO_NAOH	0.000000	0.000000
DOSE_TERT_COAG	0.000000	0.000000
DOSE_TERT_POLY	0.000000	0.000000
DOSE_TERT_NAOH	0.000000	0.000000
S_SLUD_COAG	0.1000000	0.000000
S_SLUD_POLY	1.000000	0.000000
S_SLUD_NAOH	0.000000	0.000000
CC_IN_CHEM_COD	6640.501	0.000000
CC_IN_CHEM_BOD	2908.288	0.000000
CC_IN_CHEM_N	63.41497	0.000000
CC_IN_CHEM_TDS	3734.461	0.000000
CC_IN_CHEM_TSS	3913.638	0.000000
CC_OUT_CHEM_COD	2737.553	0.000000
CC_OUT_CHEM_BOD	1370.222	0.000000
CC_OUT_CHEM_N	67.22457	0.000000
CC_OUT_CHEM_TDS	87.97345	0.000000
CC_OUT_CHEM_TSS	92.19437	0.000000
CC_IN_BIO_COD	2737.553	0.000000
CC_IN_BIO_BOD	1370.222	0.000000
CC_IN_BIO_N	67.22457	0.000000
CC_IN_BIO_TDS	87.97345	0.000000
CC_IN_BIO_TSS	92.19437	0.000000
CC_OUT_BIO_COD	155.8371	0.000000
CC_OUT_BIO_BOD	78.00085	0.000000
CC_OUT_BIO_N	15.30722	0.000000
CC_OUT_BIO_TDS	65.10334	0.000000
CC_OUT_BIO_TSS	68.22696	0.000000
CC_IN_TERT_COD	155.8371	0.000000
CC_IN_TERT_BOD	78.00085	0.000000
CC_IN_TERT_N	15.30722	0.000000
CC_IN_TERT_TDS	65.10334	0.000000
CC_IN_TERT_TSS	68.22696	0.000000
CC_OUT_TERT_COD	62.33485	0.000000
CC_OUT_TERT_BOD	31.20034	0.000000
CC_OUT_TERT_N	15.30722	0.000000
CC_OUT_TERT_TDS	58.59301	0.000000
CC_OUT_TERT_TSS	61.40427	0.000000

CC_OUT_FW_COD	10.00000	0.000000
CC_OUT_FW_BOD	6.000000	0.000000
CC_OUT_FW_N	1.000000	0.000000
CC_OUT_FW_TDS	10.00000	0.000000
CC_OUT_FW_TSS	10.00000	0.000000
CC_OUT_TRW_COD	150.0000	0.000000
CC_OUT_TRW_BOD	100.0000	0.000000
CC_OUT_TRW_N	10.00000	0.000000
CC_OUT_TRW_TDS	100.0000	0.000000
CC_OUT_TRW_TSS	100.0000	0.000000
CC_IN_RPG_COD	300.0000	0.000000
CC_IN_RPG_BOD	142.0111	0.000000
CC_IN_RPG_N	16.27971	0.000000
CC_IN_RPG_TDS	150.0000	0.000000
CC_IN_RPG_TSS	150.0000	0.000000
CC_IN_FSEP_COD	300.0000	0.000000
CC_IN_FSEP_BOD	142.0111	0.000000
CC_IN_FSEP_N	16.27971	0.000000
CC_IN_FSEP_TDS	150.0000	0.000000
CC_IN_FSEP_TSS	150.0000	0.000000
CC_IN_SIEV_COD	300.0000	0.000000
CC_IN_SIEV_BOD	142.0111	0.000000
CC_IN_SIEV_N	16.27971	0.000000
CC_IN_SIEV_TDS	150.0000	0.000000
CC_IN_SIEV_TSS	150.0000	0.000000
HC_WTP	20.10000	0.000000
PC_WTP	20.10000	0.000000
CFC_WTP	0.000000	0.000000
HUC_WTP	1827273.	0.000000
CFC_INT_WTP2RPG	0.000000	0.000000
CFC_INT_WTP2FSEP	0.000000	0.000000
CFC_INT_WTP2SIEV	20.10000	0.000000
HC_DBK	2355.800	0.000000
PC_DBK	2355.800	0.000000
CFC_DBK	0.000000	0.000000
HUC_DBK	28.31490	0.000000
TOT_OUT_DBK	83.20000	0.000000
CFC_INT_DBK2RPG	1766.850	0.000000
INT_DBK2RPG	62.40000	0.000000
HC_Y_DBK	588.9500	0.000000
DIS_DBK	20.80000	0.000000
HC_RPG	3336.878	0.000000
PC_RPG	97.00000	0.000000
CFC_RPG	3239.878	0.000000
CFC_FW2RPG	0.000000	0.000000
CFC_INT_WTP2PRG	0.000000	0.000000
CFC_FSEP2RPG	0.000000	0.000000
CFC_SIEV2RPG	31.61645	0.000000
CFC_SWSEP2RPG	6.310677	0.000000
CFC_FILT2RPG	0.000000	0.000000
CFC_WW_CHEM2RPG	5.254512	0.000000
CFC_WW_BIO2RPG	1429.846	0.000000
CFC_WW_TERT2RPG	0.000000	0.000000
HUC_FW	0.3300000	0.000000
HUC_FSEP	37.50321	0.000000
HUC_SIEV	39.72899	0.000000
HUC_SWSEP	40.22066	0.000000
HUC_FILT	40.68448	0.000000
HUC_CHEM	40.58874	0.000000
HUC_BIO	40.94887	0.000000

HUC_TERT	42.64341	0.000000
HUC_RPG	33.91136	0.000000
TOT_OUT_RPG	98.40000	0.000000
CFC_INT_RPG2FSEP	3336.878	0.000000
INT_RPG2FSEP	98.40000	0.000000
HC_FSEP	6953.095	0.000000
PC_FSEP	56.40000	0.000000
CFC_FSEP	6896.695	0.000000
CFC_FW2FSEP	0.000000	0.000000
CFC_FSEP2FSEP	0.000000	0.000000
CFC_SIEV2FSEP	76.40641	0.000000
CFC_SWSEP2FSEP	15.25080	0.000000
CFC_FILT2FSEP	0.000000	0.000000
CFC_WW_CHEM2FSEP	12.69840	0.000000
CFC_WW_BIO2FSEP	3455.461	0.000000
CFC_WW_TERT2FSEP	0.000000	0.000000
TOT_OUT_FSEP	185.4000	0.000000
CFC_INT_FSEP2SIEV	3424.043	0.000000
INT_FSEP2SIEV	91.30000	0.000000
CFC_INT_FSEP2CHEM	2962.753	0.000000
HC_Y_FSEP	566.2984	1.000000
DIS_FSEP	15.10000	0.000000
HC_SIEV	8394.735	0.000000
PC_SIEV	40.50000	0.000000
CFC_SIEV	8354.235	0.000000
CFC_FW2SIEV	0.000000	0.000000
CFC_FSEP2SIEV	0.000000	0.000000
CFC_SIEV2SIEV	105.3882	0.000000
CFC_SWSEP2SIEV	21.03559	0.000000
CFC_FILT2SIEV	0.000000	0.000000
CFC_WW_CHEM2SIEV	17.51505	0.000000
CFC_WW_BIO2SIEV	4766.153	0.000000
CFC_WW_TERT2SIEV	0.000000	0.000000
TOT_OUT_SIEV	211.3000	0.000000
CFC_INT_SIEV2SWSEP	3579.582	0.000000
INT_SIEV2SWSEP	90.10000	0.000000
CFC_INT_SIEV2CHEM	4530.230	0.000000
HC_Y_SIEV	71.51218	1.000000
DIS_SIEV	1.800000	0.000000
HC_SWSEP	3623.882	0.000000
PC_SWSEP	44.30000	0.000000
CFC_SWSEP	3579.582	0.000000
TOT_OUT_SWSEP	90.10000	0.000000
CFC_INT_SWSEP2FILT	1222.708	0.000000
INT_SWSEP2FILT	30.40000	0.000000
CFC_INT_SWSEP2CHEM	2358.577	0.000000
HC_FILT	1236.808	0.000000
PC_FILT	14.10000	0.000000
CFC_FILT	1222.708	0.000000
TOT_OUT_FILT	30.40000	0.000000
CFC_INT_FILT2DP	508.5560	0.000000
INT_FILT2DP	12.50000	0.000000
CFC_INT_FILT2CHEM	728.2522	0.000000
HC_DP	560.0560	0.000000
PC_DP	51.50000	0.000000
CFC_DP	508.5560	0.000000
HUC_DP	46.67133	0.000000
TOT_OUT_DP	12.00000	0.000000
HC_P_DP	560.0560	0.000000
P_DP	12.00000	0.000000

HC_CHEM	14036.35	0.000000
PC_CHEM	218.6395	0.000000
CFC_CHEM	13817.71	0.000000
CFC_WW_SLUD2CHEM	3237.898	0.000000
CFC_SLUD_CHEM2SLUD	2119.527	0.000000
CFC_WW_CHEM2BIO	11881.35	0.000000
HC_BIO	11986.77	0.000000
PC_BIO	105.4200	0.000000
CFC_BIO	11881.35	0.000000
CFC_SLUD_BIO2SLUD	1458.334	0.000000
CFC_WW_BIO2TERT	876.9799	0.000000
HC_TERT	913.2710	0.000000
PC_TERT	36.29109	0.000000
CFC_TERT	876.9799	0.000000
CFC_WW_TERT2DIS	913.2710	0.000000
HC_Y_TERT	913.2710	1.000000
HC_SLUD	3729.788	0.000000
PC_SLUD	151.9265	0.000000
CFC_SLUD	3577.861	0.000000
HUC_SLUD	42.46448	0.000000
CFC_SLUD_DIS	491.8895	0.000000
HC_Y_SLUD	491.8895	1.000000
COST_WASTE_MANAGEMENT	320.9623	1.000000
THC_Y	2952.883	0.000000

APPENDIX E

LINGO FILES AND RESULTS OF CHAPTER 9

CHAPTER 9

AN OPTIMISATION-BASED COOPERATIVE GAME APPROACH FOR SYSTEMATIC ALLOCATION OF COSTS AND BENEFITS IN INTERPLANT PROCESS INTEGRATION

Coding of Literature Case Study:

```
max = lambda;

CS1 = 0;     !USD/DAY;
CS2 = 0;     !USD/DAY;
CS3 = 0;     !USD/DAY;
CS4 = 0;     !USD/DAY;
CS12 = 13;
CS13 = 18;   !USD/DAY;
CS14 = 129;  !USD/DAY;
CS23 = 121;        !USD/DAY;
CS24 = 0;
CS34 = 0;
CS123 = 130;       !USD/DAY;
CS124 = 142;
CS134 = 146;
CS234 = 121;
CS1234 = 259;

x1 + x2 + x3 + x4 = CS1234;
x1 >= CS1; @free(x1);
x2 >= CS2; @free(x2);
x3 >= CS3; @free(x3);
x4 >= CS4; @free(x4);

x1/C1 >= lambda;

C1 = (CS1 + CS12 + CS13 + CS14 + CS123 + CS124 + CS134 + CS1234 -
(CS2 + CS3 + CS4 + CS23 + CS24 + CS34 + CS234))/(CS1234);
InverseC1 = 1/C1;
@free(C1); @free(InverseC1);

x2/C2 >= lambda;

C2 = (CS2 + CS12 + CS23 + CS24 + CS123 + CS124 + CS234 + CS1234 -
(CS1 + CS3 + CS4 + CS13 + CS14 + CS34 + CS134))/(CS1234);
InverseC2 = 1/C2;
@free(C2); @free(InverseC2);

x3/C3 >= lambda;

C3 = (CS3 + CS13 + CS23 + CS34 + CS123 + CS134 + CS234 + CS1234 -
(CS1 + CS2 + CS4 + CS12 + CS14 + CS24 + CS124))/(CS1234);
```

```
InverseC3 = 1/C3;
@free(C3); @free(InverseC3);

x4/C4 >= lambda;

C4 = (CS4 + CS14 + CS24 + CS34 + CS124 + CS134 + CS234 + CS1234 -
(CS1 + CS2 + CS3 + CS12 + CS13 + CS23 + CS123))/(CS1234);
InverseC4 = 1/C4;
@free(C4); @free(InverseC4);
```

Results of Literature Case Study:

```
Global optimal solution found.
Objective value:                              31.73179
Infeasibilities:                              0.000000
Total solver iterations:                             0

Model Class:                                        LP

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

Total constraints:                 10
Nonlinear constraints:              0

Total nonzeros:                    17
Nonlinear nonzeros:                 0
```

Variable	Value	Reduced Cost
LAMBDA	31.73179	0.000000
CS1	0.000000	0.000000
CS2	0.000000	0.000000
CS3	0.000000	0.000000
CS4	0.000000	0.000000
CS12	13.00000	0.000000
CS13	18.00000	0.000000
CS14	129.0000	0.000000
CS23	121.0000	0.000000
CS24	0.000000	0.000000
CS34	0.000000	0.000000
CS123	130.0000	0.000000
CS124	142.0000	0.000000
CS134	146.0000	0.000000
CS234	121.0000	0.000000
CS1234	259.0000	0.000000
X1	72.89735	0.000000
X2	60.40066	0.000000
X3	62.60596	0.000000
X4	63.09603	0.000000
C1	2.297297	0.000000
INVERSEC1	0.4352941	0.000000
C2	1.903475	0.000000
INVERSEC2	0.5253550	0.000000
C3	1.972973	0.000000
INVERSEC3	0.5068493	0.000000
C4	1.988417	0.000000
INVERSEC4	0.5029126	0.000000

Coding of Industrial Case Study:

```
max = lambda;

CS1 = 0;     !USD/DAY;
CS2 = 0;     !USD/DAY;
CS3 = 0;     !USD/DAY;
CS4 = 0;     !USD/DAY;
CS12 = 1138.22;
CS13 = 377.00;     !USD/DAY;
CS14 = 1131.05;    !USD/DAY;
CS23 = 980.22;     !USD/DAY;
CS24 = 296.13;
CS34 = 790.82;
CS123 = 2828.76;   !USD/DAY;
CS124 = 2898.72;
CS134 = 2298.87;
CS234 = 2067.17;
CS1234 = 5046.76;

x1 + x2 + x3 + x4 = CS1234;
x1 >= CS1; @free(x1);
x2 >= CS2; @free(x2);
x3 >= CS3; @free(x3);
x4 >= CS4; @free(x4);

x1/C1 >= lambda;

C1 = (CS1 + CS12 + CS13 + CS14 + CS123 + CS124 + CS134 + CS1234 -
(CS2 + CS3 + CS4 + CS23 + CS24 + CS34 + CS234))/(CS1234);
InverseC1 = 1/C1;
@free(C1); @free(InverseC1);

x2/C2 >= lambda;

C2 = (CS2 + CS12 + CS23 + CS24 + CS123 + CS124 + CS234 + CS1234 -
(CS1 + CS3 + CS4 + CS13 + CS14 + CS34 + CS134))/(CS1234);
InverseC2 = 1/C2;
@free(C2); @free(InverseC2);

x3/C3 >= lambda;

C3 = (CS3 + CS13 + CS23 + CS34 + CS123 + CS134 + CS234 + CS1234 -
(CS1 + CS2 + CS4 + CS12 + CS14 + CS24 + CS124))/(CS1234);
InverseC3 = 1/C3;
@free(C3); @free(InverseC3);

x4/C4 >= lambda;

C4 = (CS4 + CS14 + CS24 + CS34 + CS124 + CS134 + CS234 + CS1234 -
(CS1 + CS2 + CS3 + CS12 + CS13 + CS23 + CS123))/(CS1234);
InverseC4 = 1/C4;
@free(C4); @free(InverseC4);
```

Results of Industrial Case Study:

```
Global optimal solution found.
Objective value:                              630.8450
Infeasibilities:                              0.000000
Total solver iterations:                             0

Model Class:                                        LP

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

Total constraints:                 10
Nonlinear constraints:              0

Total nonzeros:                    17
Nonlinear nonzeros:                 0
```

Variable	Value	Reduced Cost
LAMBDA	630.8450	0.000000
CS1	0.000000	0.000000
CS2	0.000000	0.000000
CS3	0.000000	0.000000
CS4	0.000000	0.000000
CS12	1138.220	0.000000
CS13	377.0000	0.000000
CS14	1131.050	0.000000
CS23	980.2200	0.000000
CS24	296.1300	0.000000
CS34	790.8200	0.000000
CS123	2828.760	0.000000
CS124	2898.720	0.000000
CS134	2298.870	0.000000
CS234	2067.170	0.000000
CS1234	5046.760	0.000000
X1	1448.130	0.000000
X2	1332.280	0.000000
X3	1115.685	0.000000
X4	1150.665	0.000000
C1	2.295540	0.000000
INVERSEC1	0.4356273	0.000000
C2	2.111898	0.000000
INVERSEC2	0.4735078	0.000000
C3	1.768556	0.000000
INVERSEC3	0.5654329	0.000000
C4	1.824006	0.000000
INVERSEC4	0.5482438	0.000000