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

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

Keywords: Empty Fruit Bunch; biomass supply chain; superstructure optimization; mixed integer programming

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1. Introduction

Palm oil industries have played significant roles in the socio-economic developments in Malaysia. Since 1960, Malaysia has been one of the major producers and exporters of palm oil [1]. Statistics have shown that the palm oil sector has contributed 12% of total Malaysia's export, and this percentage was equivalent to RM 80.4 billion [2] or about USD 18.26 billion in current currency conversion. In terms of social and rural improvements, the establishment of the Federal Land Development Authority (FELDA) in 1956 has carried out landless resettlements mainly for palm oil plantations in the country that benefited almost 113,000 low-income families [3]. This effort has not only alleviated poverty in the country but also reduced economic imbalances between urban and rural populations [4].

As palm oil is one of the most important sources of vegetable oils, the demand for it is increasing with the proliferative growth of the human population globally. Interestingly, significant uses of palm oils for cooking and manufacturing oleo-chemicals have been annexed with the production of biodiesel recently. In this context, Malaysia's Ministry of Plantation Industries and Commodities intends to mandate 20% blending of palm-based biodiesel with petro-based diesel instead of 5% blending before November 2014. This move has further increased the economic gains of palm oil, especially in situations where petroleum prices are unduly high.

Palm oil plantations also produce agricultural biomass such as EFB. Although it was once considered a low-value residue, technological advances started to convert this biomass into numerous types of bio-based products. The scenario has created considerable amounts of enterprising companies to venture into these waste-to-wealth businesses throughout the country. However, to plan and operate any EFB utilization project successfully, the supply chain that includes optimal decisions for process and transportation is one of the key considerations. With numerous alternatives available, selecting the best processing route for producing a product is an important decision to make because of several associated factors such as the product's competitiveness, the viability and status of technology, the social and environmental impacts, and so on. In this regard, Figure 1 depicts technological and resource-to-product selection dilemmas that typically occur in any biomass supply chain. Furthermore, the figure also has options to sell the produced products directly or to further refine them as shown by the dash lines.

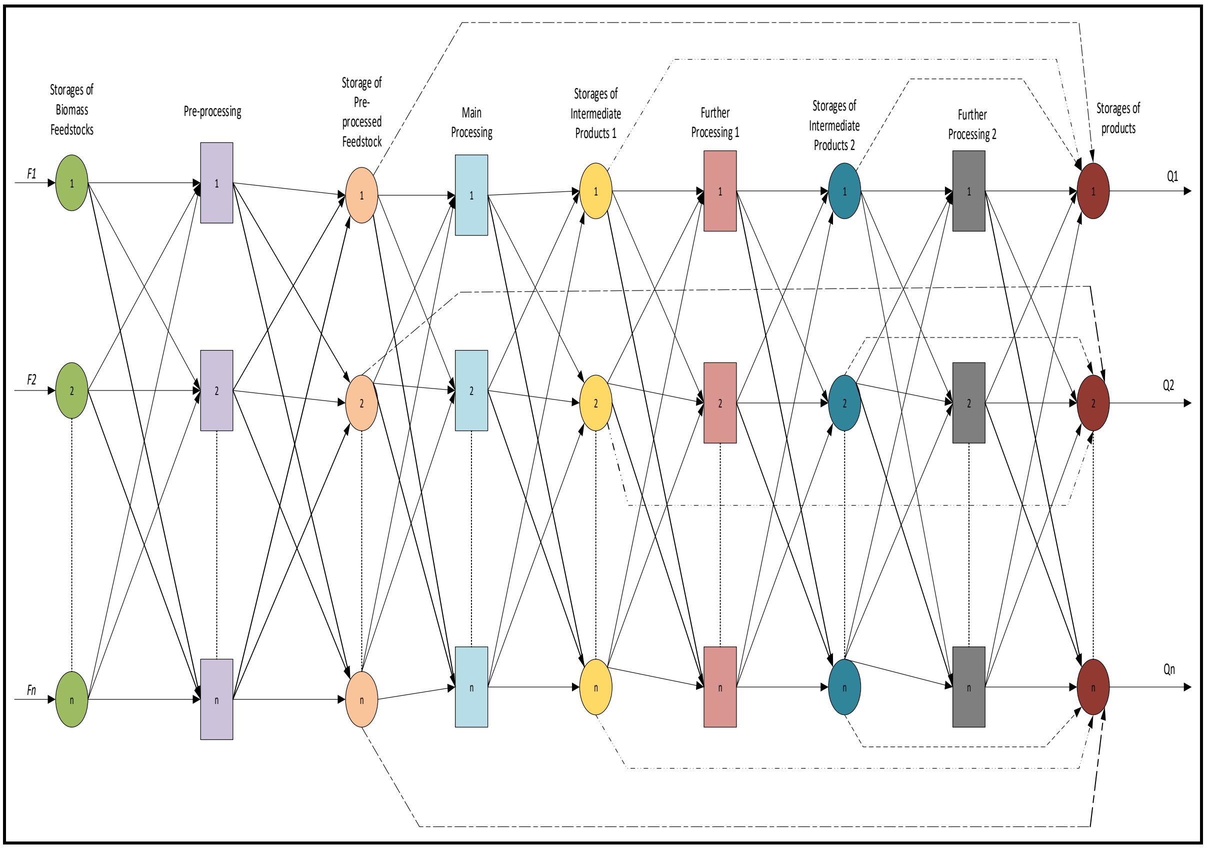


Figure 1. Selection dilemmas in the biomass supply chain.

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

Previous studies about MIP modeling of the biomass supply chain have been published by several authors. Recently, [5] had reviewed the optimization biomass supply chain optimization model streamed to the formulation gaps. These include modeling off biomass sources for energy purposes through combustion [6]; a hybrid of gasification and fermentation processes of agricultural residues and dedicated crops for bio-ethanol production [7]; bio-ethanol production from agricultural residues and municipal solid wastes by considering policy standards and conversion technologies [8]; agricultural residues for bioethanol production via a bio-chemical route only by considering enzymatic hydrolysis and acidic hydrolysis [9]; multi-objective optimization for gasoline and bio-diesel productions by using combinations of forestry residues, agricultural residues, and dedicated crops [10]; and oil seed crop for the productions of energy products such as biodiesel, heat, power, and syngas [11]. In recent studies, [12] have modeled the biofuel supply chain from corn stover by using a fast pyrolysis process. They have considered different biomass supplies and demands with biofuel supply shortage penalty and storage costs in the model. [13] have optimized a biofuel supply chain model that integrates strategic and tactical planning decisions. Key strategic decisions were numbers, locations, capacities, and distribution patterns for biomass and ethanol, while biomass production and delivery were among the tactical decisions. [14] have developed an optimization model of the supply chain for bioelectricity production from forest residues in Portugal. The objective function has minimized the total supply chain cost and optimally selected biomass amounts and sources. For recent studies, [15] developed a model that provides and considers options in a biomass-to-bioproducts supply chain to produce multiple products. [16] had integrated a multi-objective optimization model with a fuzzy-Analytic Hierarchy process in their palm oil mill biomass supply chain model, while [17] had extended the palm oil mill biomass cogeneration supply chain into operation and maintenance consideration in their optimization model. Some of the authors have expanded into stochastic modeling [18].

The above-mentioned studies have modeled the biomass supply chain problem as Mixed Integer Linear Programming (MILP) models, while the present paper considers nonlinearities in the problem which will lead to a Mixed Integer Non-linear Programming (MINLP) model. Thus, this research implication was revealed through the attainment of a method to linearize certain nonlinear models. According to [19] the optimization modeler keeps exploring the linearization method of the complex optimization problem to reduce the modeling time. A new method for linearization of certain nonlinear constraints in the linear optimization model was developed by [20]. The model in this study is an extension of our previous model [21] to make it more comprehensive and extensive. In this model, the objective was to maximize the profit of EFB's supply chain for multi-product productions which would provide optimal decisions regarding biomass amounts, process and production levels, the product's direct sales or further refinements, transportation modes at each processing stage, as well as environmental considerations from both productions and transportations. The rationale behind conducting this extended optimization model is directed towards the prosperous biomass industry. This study is pursued to develop a comprehensive decision-making tool for future investments in palm oil biomass projects that require decisive selection of those mentioned considerations. One of the optimization model implications is to motivate industrial player to invest in a biomass project such as a palm oil mill-based cogeneration system. It also acts as a tool for energy policy makers to support biomass utilization in some countries that have abundant resources of biomass such as Malaysia and Indonesia.

2. Materials and Methods

To model and optimize the EFB's supply chain, a methodology that is shown in Figure 2 was followed. This study has extended the previous optimization model from [21] to include integer variables for important decisions related to selections of best processes and transportation modes. Each decision was effective for each processing stage (pre-processing, main processing, further processing 1, and further processing 2) in the supply chain.

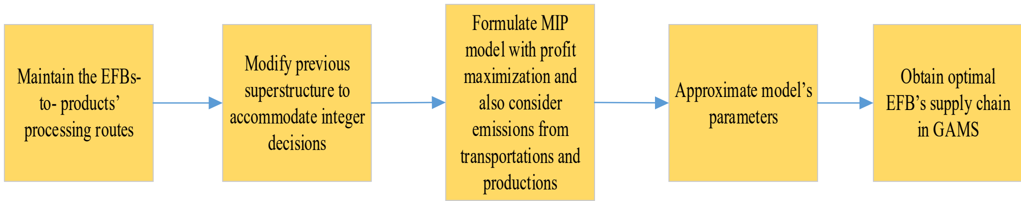


Figure 2. Methodology for EFB's supply chain with optimal processing route and transportation mode.

Figure 3 shows the modified superstructure of EFB's supply chain. Each segment of transportation was assigned with relevant modes of transportation. Solid biomass and product transportations to the next processing stages would utilize either truck, train, or barge, while transportation of liquid or gaseous products would use the pipeline automatically. Square shapes in the superstructure represent processing facilities while storages are represented by the oval shapes. The black solid arrows show processing sequences while the black dash lines give indications to sell the products from storage directly to the customers. The curve arrows represent option for selling of the products at *i*, *k* and *m*. The extraction process was divided into three (extraction 1–3), acid hydrolysis into two (acid hydrolysis 1 and 2), enzymatic process into two (enzymatic hydrolysis 1 and 2), bio-oil upgrading into two (bio-oil upgrading 1 and 2), and lastly FTL production into two (FTL production 1 and 2).

These divisions are shown with a square shape in Figure 3 with more than one product except for power production with the products (electricity, MP steam, and LP steam) produced from a single unit process. The reason behind these divisions was to ensure the model could decide on the optimal processing routes and their transportation modes, as well as to ensure the explanations could be established clearly. Similar to the previous superstructure, the extended superstructure shows competitive utilizations and routes for EFB, cellulose, hemicellulose, pellet, torrefied pellet, glucose, xylose, bio-syngas, and bio-oil. In addition, it assumed homogenous blending of EFBs from different collection points.

Overall, there were four stages of processing (*h*, *j*, *l*, and *n*) and four segments of transportations (*g* to *h*, *h* to *j*, *j* to *l*, and *l* to *n*). Table 1 contains lists of the indices such as *g*, *h*, *j*, *l*, and *p*, which will be used in the model's formulations and lists of further aspects for each of the indices.

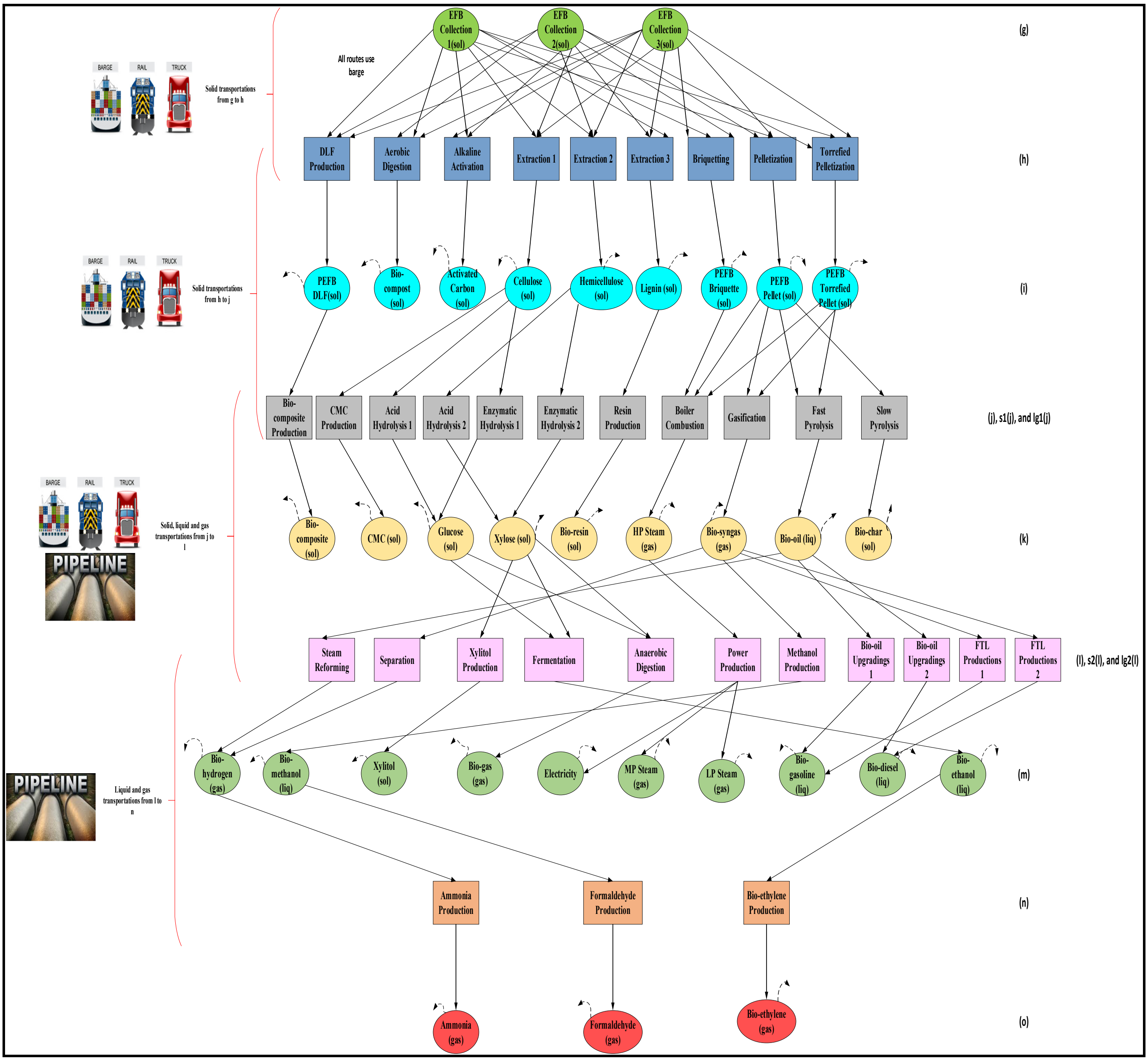


Figure 3. Superstructure of EFB's supply chain for selecting optimal processing routes and transportation modes.

Table 1. List of indices and descriptions for the model's formulations.

Indices	Description	Contents
g	Biomass source storage locations	EFB1, EFB2, and EFB3.
h	Pre-processing facilities	DLF production, aerobic digestion, alkaline activation, extraction 1, extraction 2, extraction 3, briquetting, pelletization, and torrefied pelletization.
j	Main processing facilities	Bio-composite production, CMC production, acid hydrolysis 1, acid hydrolysis 2, enzymatic hydrolysis 1, enzymatic hydrolysis 2, resin production, boiler combustion, gasification, fast pyrolysis, and slow pyrolysis.
l	Further processing 1 facilities	Steam reforming, separation, xylitol production, fermentation, anaerobic digestion, power production, methanol production, bio-oil upgrading 1, bio-oil upgrading 2, FTL production 1, and FTL production 2.
n	Further processing 2 facilities	Ammonia production, formaldehyde production, and bio-ethylene production.
p	Product sum up type p storages and to the users	PEFB-DLF, bio-compost, activated carbon, cellulose, hemicellulose, lignin, PFB briquette, PEFB pellet, PEFB torrefied pellet, bio-composite, CMC, glucose, xylose, bio-resin, HP steam, bio-syngas, bio-oil, bio-char, bio-hydrogen, xylitol, bio-ethanol, bio-gas, bio-methanol, electricity, MP steam, LP steam, bio-ethylene, bio-diesel, bio-gasoline, ammonia, and formaldehyde.
Further aspects of the indices and descriptions for the model's formulation		
$i(p)$	Pre-processed feedstocks storages	PEFB-DLF, bio-compost, activated carbon, cellulose, hemicellulose, lignin, PFB briquette, PEFB pellet, and PEFB torrefied pellet.
$k(p)$	Intermediate products 1 storages	Bio-composite, CMC, glucose, xylose, bio-resin, HP steam, bio-syngas, bio-oil, and bio-char.
$lg2(l)$	Further processing 1 facilities for solid solution and liquid and gaseous feeds	Steam reforming, separation, power production, MP steam production, LP steam production, methanol production, bio-oil upgrading 1, bio-oil upgrading 2, FTL production 1, FTL production 2, and fermentation.
$lg1(j)$	Main processing facilities for liquid and gaseous products to the next processing facilities	Boiler combustion, gasification, and fast pyrolysis.
$m(p)$	Intermediate products 2 storages	Bio-hydrogen, xylitol, bio-ethanol, bio-gas, bio-methanol, electricity, MP steam, LP steam, bio-diesel, and bio-gasoline.
$o(p)$	Final products storages	Ammonia, formaldehyde, and bio-ethylene.
$s1(j)$	Main processing facilities for solid products to the next processing facilities	Acid hydrolysis 1, acid hydrolysis 2, enzymatic hydrolysis 1, and enzymatic hydrolysis 2.
$s2(l)$	Further processing 1 facilities for solid feeds	Xylitol production and anaerobic digestion.
t	Truck, train, and barge transportation	Truck, train, and barge.
z	Pipeline transportation	Pipeline.

3. Mathematical Model for the Optimal Selections

Formulations of the mathematical model to optimize the EFB's supply chain were written by the following equations, which are each explained in Tables 2 and 3.

Table 2. Description of formulations (1) to (58).

Formulation	Description
1	Objective function
2	Equation to calculate total sales of products in USD per year
3	Equation to calculate total EFB costs in USD per year
4	Components in transportation operating costs
5	Equation to calculate transportation operating costs for truck, train, and barge in USD per year
6	Equation to calculate transportation operating costs for pipeline in USD per year
7	Total amount of biomass transported from g to h using transportation t in tonnes per year
8	Total amount of pre-processed products transported from h to j using transportation t in tonnes per year
9	Total amount of solid intermediate products 1 transported from $s1(j)$ to $s2(l)$ using transportation t in tonnes per year
10	Total amount of liquid and gaseous intermediate products 1 transported from $lg1(j)$ to $lg2(l)$ using transportation z in tonnes per year
11	Total amount of intermediate products 2 transported from $lg2(l)$ to n using transportation z in tonnes per year
12	Equation to calculate production cost in USD per year
13	Components in emission treatment costs
14	Equation to calculate emission treatment costs from productions in USD per year
15	Equation to calculate emission treatment costs from transportations in USD per year
16	Equation to calculate emission at h to produce i in tonnes CO_2 equivalent per year
17	Equation to calculate emission at j to produce k in tonnes CO_2 equivalent per year
18	Equation to calculate emission at $s2(l)$ to produce m in tonnes CO_2 equivalent per year
19	Equation to calculate emission at $lg2(l)$ to produce m in tonnes CO_2 equivalent per year
20	Equation to calculate emission at n to produce o in tonnes CO_2 equivalent per year
21	Equation to calculate emission from transportation between g and h using transportation mode t in tonnes CO_2 equivalent per year
22	Equation to calculate emission from transportation between h and j using transportation mode t in tonnes CO_2 equivalent per year
23	Equation to calculate emission from transportation between j and $s2(l)$ using transportation mode t in tonnes CO_2 equivalent per year
24	Amount of EFB in tonnes per year must not exceed the availability
25	Range of amounts of produced products in tonnes or MWh per year
26	Mass balance for EFB sources' storage outlets in tonnes per year
27	Mass balance for yield of pre-processed feedstocks in tonnes per year
28	Mass balance for pre-processing facilities outlets in tonnes per year
29	Mass balance for yield of intermediate products 1 in tonnes per year
30	Mass balance for main processing facilities outlets in tonnes per year
31	Mass balance for yield of intermediate products 2 from solid feeds in tonnes per year
32	Mass balance for yield of intermediate products 2 from solid solution and liquid and gaseous feeds in tonnes per year
33	Mass balance of $s2(l)$ in tonnes per year
34	Mass balance of $lg2(l)$ in tonnes per year
35	Mass balance for yield of final products in tonnes per year
36	Mass balance for further processing facilities 2 outlets in tonnes per year
37	Summation of products at i in tonnes per year
38	Summation of products at k in tonnes per year
39	Summation of products at m in tonnes per year
40	Summation of products at o in tonnes per year

Table 2. *Cont.*

Formulation	Description
41	Maximum capacity for transportation t from g to h in tonnes per year
42	Maximum capacity for transportation t from h to j in tonnes per year
43	Maximum capacity for transportation t for solid from j to l in tonnes per year
44	Maximum capacity for transportation z for liquid and gas from j to l in tonnes per year
45	Maximum capacity for transportation z for liquid and gas from l to n in tonnes per year
46	Integer decision for mode of transportation from g to h
47	Integer decision for mode of transportation from h to j
48	Integer decision for mode of transportation from $s1(j)$ to $s2(l)$
49	Integer decision for mode of transportation from $lg1(j)$ to $lg2(l)$
50	Integer decision for mode of transportation from $lg2(l)$ to n
51	Integer decision for best processing route at h to produce i
52	Integer decision for best processing route at j to produce k
53	Integer decision for best processing route at $s2(l)$ to produce m
54	Integer decision for best processing route at $lg2(l)$ to produce m
55	Summation for transporting solid fraction X using transportation t
56	Summation for transporting liquid and gas fractions ZZ using transportation z
57	Upper and lower limits of capacity for transportation t at each processing route
58	Upper and lower limits of capacity for transportation z at each processing route

Table 3. Descriptions of terms used in formulations (1) to (58).

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

Table 3. *Cont.*

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

Table 3. *Cont.*

Term	Category	Description
$FTL_{lg2.m.n}$	Decision variable	Amount of intermediate products 2 m transported from further processing 1 facilities $lg2(l)$ to further processing 2 facilities n in tonnes per year
$FPH_{h,i}$	Decision variable	Amount of pre-processed feedstocks i produced from biomass feedstocks g through pre-processing facilities h in tonnes per year
$FPJ_{i,j,k}$	Decision variable	Amount of intermediate product 1 k produced from pre-processed feedstocks i through main processing facilities j in tonnes per year
$FPL\_S_{k,s2,m}$	Decision variable	Amount of intermediate products 2 m produced from intermediate products 1 k through further processing 1 facilities $S2(l)$ in tonnes per year
$FPL\_LG_{k,lg2,m}$	Decision variable	Amount of intermediate products 2 m produced from intermediate products 1 k through further processing 1 facilities $lg2(l)$ in tonnes per year
$FPN_{m,n,o}$	Decision variable	Amount of final products o produced from intermediate products 2 m through further processing 2 facilities n in tonnes per year
$FEVH_{h,i}$	Decision variable	Amount of emission at h to produce i in tonnes CO_2 equivalent per year
$FEVJ_{i,j,k}$	Decision variable	Amount of emission at j to produce k in tonnes CO_2 equivalent per year from i
$FEVL\_S_{k,s2,m}$	Decision variable	Amount of emission at $s2(l)$ to produce m in tonnes CO_2 equivalent per year from k
$FEVL\_LG_{k,lg2,m}$	Decision variable	Amount of emission at $lg2(l)$ to produce m in tonnes CO_2 equivalent per year from k
$FEVN_{m,n,o}$	Decision variable	Amount of emission at n to produce o in tonnes CO_2 equivalent per year from m
$FTFTE_{g,h,t}$	Decision variable	Amount of emission from transportation between g and h in tonnes CO_2 equivalent per year using transportation t
$FTHTE_{h,j,t}$	Decision variable	Amount of emission from transportation between h and j in tonnes CO_2 equivalent per year using transportation t
$FTJTE\_S_{j,s2,t}$	Decision variable	Amount of emission from transportation between j and $s2(l)$ in tonnes CO_2 equivalent per year using transportation t
$Y1_{h,i}$	Binary variable	Binary variable for best production route from g to i through h
$FSH_{h,i}$	Decision variable	Amount of pre-processed feedstocks i produced from pre-processing facilities h to be sold directly in tonnes per year
$Y2_{i,j,k}$	Binary variable	Binary variable for best production route from i to k through j
$FSJ_{j,k}$	Decision variable	Amount of intermediate products 1 k produced from main processing facilities j to be sold directly in tonnes per year
$Y3a_{k,s2,m}$	Binary variable	Binary variable for best production route from k to m through $s2(l)$
$Y3b_{k,lg2,m}$	Binary variable	Binary variable for best production route from k to m through $lg2(l)$
$FSL\_S_{s2,m}$	Decision variable	Amount of intermediate products 2 m produced from intermediate products 1 k through further processing 1 facilities $s2(l)$ to be sold directly in tonnes per year
$FSL\_LG_{lg2,m}$	Decision variable	Amount of intermediate products 2 m produced from intermediate products 1 k through further processing 1 facilities $lg2(l)$ to be sold directly in tonnes per year
$FSN_{n,o}$	Decision variable	Amount of final products o produced from intermediate products 2 m through further processing 2 facilities n to be sold in tonnes per year

Table 3. *Cont.*

Term	Category	Description
Q_i	**Decision variable**	**Amount of pre-processed feedstocks stored and ready for sales in tonnes per year at *i***
Q_k	**Decision variable**	**Amount of intermediate products 1 stored and ready for sales in tonnes per year at *k***
Q_m	**Decision variable**	**Amount of intermediate products 2 stored and ready for sales in tonnes per year at *m***
Q_o	**Decision variable**	**Amount of intermediate products 2 stored and ready for sales in tonnes per year at *o***
$TMAXC_t$	**Parameter**	**Maximum capacity in tonnes per year for transportation *t* at each processing route**
$YGH_{g,h,t}$	**Binary variable**	**Binary variable for best transportation *t* from stage *g* to stage *h***
$X1_t$	**Binary variable**	**Transportation of solid fraction from stage *g* to stage *h***
$YHJ_{h,j,t}$	**Binary variable**	**Binary variable for best transportation *t* from *h* to *j***
$X2_t$	**Binary variable**	**Transportation of solid fraction from *h* to *j***
$YJL\_S_{s1,s2,t}$	**Binary variable**	**Binary variable for best transportation *t* from *s*1(*j*) to *s*2(*l*)**
$X3_t$	**Binary variable**	**Transportation of solid fraction from *stage j* to stage *l***
$PMAXC_t$	**Parameter**	**Maximum capacity in tonnes per year for transportation *z* at each processing route**
$YJL\_LG_{lg1,lg2,z}$	**Binary variable**	**Binary variable for best transportation *z* from *lg*1(*j*) to *lg*2(*l*)**
$ZZ1_z$	**Variable**	**Transportation of liquid and gaseous fractions from *j* to *l***
$YLN_{lg2,n,z}$	**Binary variable**	**Binary variable for best transportation *z* from *lg3(l)* to *n***
$ZZ2_z$	**Variable**	**Transportation of liquid and gaseous fractions from *l* to *n***

Maximize Profit = Maximize (Sales of products − Biomass cost − Transportation operating cost − Production cost − Emission treatment cost) (1)

$$Sales\ of\ products = \sum_{p=1}^{P} \boldsymbol{Q_p} * Products'\ selling\ price \quad (2)$$

$$Biomass\ cost = \sum_{g}^{G} \boldsymbol{F_g} * EFB\ Cost \quad (3)$$

Transportation operating cost = Truck, train, and barge transportation operating cost + pipeline transportation operating cost (4)

$$Truck,\ train,\ and\ barge\ transportation\ operating\ cost = \sum_t^T ((OPCOSTM_t * \sum_g^G \sum_h^H \boldsymbol{FTFT_{g,h,t}} * 2 * DGH_{g,h}) + (OPCOSTM_t * \sum_h^H \sum_j^J \boldsymbol{FTHT_{h,j,t}} * 2 * DHIJ_{h,j}) + (OPCOSTM_t * \sum_j^J \sum_{s2}^{S2} \boldsymbol{FTJT_{Sj,s2,t}} * 2 * DJKL_{Sj,s2}) \quad (5)$$

$$\boldsymbol{Pipeline\ transportation\ operating\ cost} = \sum_z^Z ((\boldsymbol{OPCOSTP_z} * \sum_j^J \sum_{lg2}^{LG2} \boldsymbol{FTJT\_LG_{j,lg2,z}} * \boldsymbol{DJKL\_LG_{j,lg2}}) + (\boldsymbol{OPCOSTP_z} * \sum_{lg2}^{LG2} \sum_n^N \boldsymbol{FTLT_{lg2,n,z}} * \boldsymbol{DLMN_{lg2,n}}) \quad (6)$$

The values of operating cost factors for each transportation mode were obtained from studies by [22]. This cost might include the salaries and wages, fuel, maintenance, etc., while the exact values in USD per tonne per km are much dependent on the types and densities of the transported products. Operating costs for solid transportation using truck, train, and barge were calculated for return trips, while for liquid and gas transportation through the pipeline were not. Further, Formulations (7)–(11) detail the loads for transportations.

$$\sum_t^T \boldsymbol{FTFT_{g,h,t}} = \boldsymbol{FTF_{g,h}} \quad (7)$$

$$\sum_t^T \boldsymbol{FTHT_{h,j,t}} = \sum_i^I \boldsymbol{FTH_{h,i,j}} \quad (8)$$

$$\sum_t^T \boldsymbol{FTJT\_S_{s1s2}} = \sum_k^K \boldsymbol{FTJ\_S_{s1,k,s2}} \tag{9}$$

$$\sum_z^Z \boldsymbol{FTJTLG_{lg1,lg2,z}} = \sum_k^K \boldsymbol{FTJ\_LG_{lg1,k,lg2}} \tag{10}$$

$$\sum_z^Z \boldsymbol{FTLT_{lg2,n,z}} = \sum_m^M \boldsymbol{FTL_{lg2.m.n}} \tag{11}$$

Production cost and emission treatment cost were also included in the model, described mathematically by (12) to (23). The production cost was the result of multiplication between flowrate and production cost factor. Production cost factor was the cost in USD to produce one unit capacity of product. Approximation of values for these factors were done in every processing unit in the processing facilities because they were difficult to be obtained in exact values. The costs for treating emissions from transportation and production activities in the supply chain have indicated that the environmental performances were considered simultaneously. It used USD 40 per tonnes of CO_2 equivalent for emission cost as per the previous model. Equations (16)–(23) represent the mass balances for the emissions that were written in tonnes CO_2 equivalent per year.

$$\begin{gathered} Production\ cost = \left(\sum_h^H \sum_i^I \boldsymbol{FPH_{h,i}} * PROCH_{h,i}\right) + \left(\sum_i^I \sum_j^J \sum_k^K \boldsymbol{FPJ_{i,j,k}} * PROCJ_{i,j,k}\right) + \left(\sum_k^K \sum_{s2}^{S2} \sum_m^M \boldsymbol{FPL\_S_{k,s2,m}} * \right. \\ \left. PROCL\_S_{k,s2,m}\right) + \left(\sum_{lg2}^{LG2} \sum_m^M \boldsymbol{FPL\_LG_{k,lg2,m}} * PROCL\_LG_{k,lg2,m}\right) + \left(\sum_m^M \sum_n^N \sum_o^O \boldsymbol{FPN_{m,n,o}} * PROCN_{m,n,o}\right) \end{gathered} \tag{12}$$

$$\begin{gathered} \boldsymbol{Emission\ treatment\ cost = emission\ treatment\ cost\ from\ production +} \\ \boldsymbol{emission\ treatment\ cost\ from\ production} \end{gathered} \tag{13}$$

$$\begin{gathered} \boldsymbol{Emission\ treatment\ cost\ from\ production} = \left[\left(\sum_h^H \sum_i^I \boldsymbol{FEVH_{h,i}}\right) + \left(\sum_i^I \sum_j^J \sum_k^K \boldsymbol{FEVJ_{i,j,k}}\right) + \right. \\ \left. \left(\sum_k^K \sum_{s2}^{S2} \sum_m^M \boldsymbol{FEVL\_S_{k,s2,m}}\right) + \left(\sum_{lg2}^{LG2} \sum_m^M \boldsymbol{FEVL\_LG_{k,lg2,m}}\right) + \left(\sum_m^M \sum_n^N \sum_o^O \boldsymbol{FEVN_{m,n,o}}\right)\right] * \boldsymbol{ET\_cost} \end{gathered} \tag{14}$$

$$\begin{gathered} \boldsymbol{Emission\ treatment\ cost\ from\ transportation} = \left[\left(\sum_g^G \sum_h^H \sum_t^T \boldsymbol{FTFTE_{g,h,t}}\right) + \left(\sum_h^H \sum_j^J \sum_t^T \boldsymbol{FTHTE_{h,j,t}}\right) + \right. \\ \left. \left(\sum_j^J \sum_{s2}^{S2} \sum_t^T \boldsymbol{FTJTE\_S_{j,s2,t}}\right)\right] * \boldsymbol{ET\_cost} \end{gathered} \tag{15}$$

$$\boldsymbol{FEVH_{h,i}} = \boldsymbol{FPH_{h,i}} * \boldsymbol{ENVH_{h,i}} \tag{16}$$

$$\boldsymbol{FEVJ_{i,j,k}} = \boldsymbol{FPJ_{i,j,k}} * \boldsymbol{ENVJ_{i,j,k}} \tag{17}$$

$$\boldsymbol{FEVL\_S_{k,s2,m}} = \boldsymbol{FPL\_S_{k,s2,m}} * \boldsymbol{ENVL\_S_{k,s2,m}} \tag{18}$$

$$\boldsymbol{FEVL\_LG_{k,lg2,m}} = \boldsymbol{FPL\_LG_{k,lg2,m}} * \boldsymbol{ENVL\_LG_{k,lg2,m}} \tag{19}$$

$$\boldsymbol{FEVN_{m,n,o}} = \boldsymbol{FPN_{m,n,o}} * \boldsymbol{ENVN_{m,n,o}} \tag{20}$$

$$\boldsymbol{FTFTE_{g,h,t}} = \boldsymbol{FTFT_{g,h,t}} * \boldsymbol{EMFAC_t} * \boldsymbol{DGH_{g,h}} \tag{21}$$

$$\boldsymbol{FTHTE_{h,j,t}} = \boldsymbol{FTHT_{h,j,t}} * \boldsymbol{EMFAC_t} * \boldsymbol{DHIJ_{h,j}} \tag{22}$$

$$\boldsymbol{FTJTE\_S_{j,s2,t}} = \boldsymbol{FTJT\_S_{j,s2,t}} * \boldsymbol{EMFAC_t} * \boldsymbol{DJKL\_S_{j,s2}} \tag{23}$$

The amount of EFB feedstock at location g must not exceed the total availability. This has considered the leftovers of EFBs in the fields. In addition, the demands for each of the products p that were produced must be met. These are described by the following constraints:

$$\sum_g^G \boldsymbol{F_g} \leq Biomass\ Availability \tag{24}$$

$$Five\ percent\ of\ World\ Demands \geq Q_p \geq Bioproduct's\ Demand \tag{25}$$

The other mass balances were represented by (26) to (40) which comprise an inequality and equalities. Multiplications of continuous and discrete (binary) variables for (27), (29), (31), (32), and (41) to (45) have caused the model to be MINLP [23]. High computational time is the typical issue with this type of programming. Methods for solving MINLP models have been reported by [24] that included branch and bound method, generalized benders decomposition, outer approximation, LP/NLP-based branch and bound, and extended cutting plane method. For this study, however, the optimization solver Branch-And-Reduce Optimization Navigator (BARON) that is available in GAMS was used for solving the MINLP.

$$\sum_h^H \boldsymbol{FTF_{g,h}} \leq F_g \tag{26}$$

$$\sum_g^G \boldsymbol{FTF_{g,h}} * CONVH_{h,i} * \boldsymbol{Y1_{h,i}} = \boldsymbol{FPH_{h,i}} \tag{27}$$

$$\boldsymbol{FPH_{h,i}} = \sum_j^J \boldsymbol{FTH_{h,i,j}} + \boldsymbol{FSH_{h,i}} \tag{28}$$

$$\sum_h^H \boldsymbol{FTH_{h,i,j}} * CONVJ_{i,j,k} * \boldsymbol{Y2_{i,j,k}} = \boldsymbol{FPJ_{i,j,k}} \tag{29}$$

$$\sum_i^I \boldsymbol{FPJ_{i,j,k}} = \boldsymbol{FSJ_{j,k}} + \sum_{s2}^{S2} \boldsymbol{FTJ\_S_{j,k,s2}} + \sum_{lg2}^{LG2} \boldsymbol{FTJ\_LG_{j,k,lg2}} \tag{30}$$

$$\sum_j^J \boldsymbol{FTJ\_S_{j,k,s2}} * CONVL\_S_{k,s2,m} * \boldsymbol{Y3a_{k,s2,m}} = \boldsymbol{FPL\_S_{k,s2,m}} \tag{31}$$

$$\sum_j^J \boldsymbol{FTJ\_LG_{j,k,lg2}} * CONVL\_LG_{k,lg2,m} * \boldsymbol{Y3b_{k,lg2,m}} = \boldsymbol{FPL\_LG_{k,lg2,m}} \tag{32}$$

$$\sum_k^K \boldsymbol{FPL\_S_{k,s2,m}} = \boldsymbol{FSL\_S_{s2,m}} \tag{33}$$

$$\sum_k^K \boldsymbol{FPL\_LG_{k,lg2,m}} = \boldsymbol{FSL\_LG_{lg2,m}} + \sum_n^N \boldsymbol{FTL_{lg2,m,n}} \tag{34}$$

$$\sum_{lg2}^{LG2} \boldsymbol{FTL_{lg2,m,n}} * CONVN_{m,n,o} = \boldsymbol{FPN_{m,n,o}} \tag{35}$$

$$\sum_m^M \boldsymbol{FPN_{m,n,o}} = \boldsymbol{FSN_{n,o}} \tag{36}$$

$$\sum_h^H \boldsymbol{FSH_{h,i}} = \boldsymbol{Q_i} \tag{37}$$

$$\sum_j^J \boldsymbol{FSJ_{j,k}} = \boldsymbol{Q_k} \tag{38}$$

$$\sum_{s2}^{S2} \boldsymbol{FSL\_S_{s2,m}} + \sum_{lg2}^{LG2} \boldsymbol{FSL\_LG_{lg2,m}} = \boldsymbol{Q_m} \tag{39}$$

$$\sum_n^N \boldsymbol{FSN_{n,o}} = \boldsymbol{Q_o} \tag{40}$$

$$\boldsymbol{FTFT_{g,h,t}} \leq TMAXC_t * \boldsymbol{YGH_{g,h,t}} * \boldsymbol{X1_t} \tag{41}$$

$$\boldsymbol{FTHT_{h,j,t}} \leq TMAXC_t * \boldsymbol{YHJ_{h,j,t}} * \boldsymbol{X2_t} \tag{42}$$

$$\boldsymbol{FTJT\_S_{s1,s2,t}} \leq TMAXC_t * \boldsymbol{YJL\_S_{s1,s2,t}} * \boldsymbol{X3_t} \tag{43}$$

$$FTJT\_LG_{lg1,lg2,z} \leq PMAXC_t * \boldsymbol{YJL\_LG_{lg1,lg2,z}} * \boldsymbol{ZZ1_z} \tag{44}$$

$$\boldsymbol{FTLT_{lg2,n,z}} \leq PMAXC_t * \boldsymbol{YLN_{lg2,n,z}} * \boldsymbol{ZZ2_z} \tag{45}$$

Binary variables will produce either 1 for selection or 0 for not. Formulations (46)–(50) would be for selecting the transportation mode, while (50)–(54) would be for the processing route.

$$\sum_t^T \boldsymbol{YGH_{g,h,t}} \leq 1 \tag{46}$$

$$\sum_t^T \boldsymbol{YHJ_{h,j,t}} \leq 1 \tag{47}$$

$$\sum_t^T \boldsymbol{YJL_{s1,s2,t}} \leq 1 \tag{48}$$

$$\sum_z^Z \boldsymbol{YJL\_L_{lg1,lg2,z}} \leq 1 \tag{49}$$

$$\sum_z^Z \boldsymbol{YLN_{lg2,n,z}} \leq 1 \tag{50}$$

$$\sum_i^I \boldsymbol{Y1_{h,i}} \leq 1 \tag{51}$$

$$\sum_{k}^{K} \boldsymbol{Y2}_{\boldsymbol{i,j,k}} \leq 1 \quad (52)$$

$$\sum_{m}^{M} \boldsymbol{Y3a}_{\boldsymbol{k,s2,m}} \leq 1 \quad (53)$$

$$\sum_{m}^{M} \boldsymbol{Y3b}_{\boldsymbol{k,lg2,m}} \leq 1 \quad (54)$$

It was an intention in this paper to assign the modes of transportation according to the physical state of the products, which in turn depends closely on the stage of processing. Stage h would only produce solid products, stages j and l would produce solid, liquid, and gaseous products, and stage n would produce only gaseous products. Therefore, transportation from g to h would involve only solids; from h to j would again involve only solids; from j to l would involve solids, liquids, and gases; from l to n would involve liquids and gas; and lastly there is no transportation required after n. In addition, the model has not considered transportation for every direct-sales product. Equations (55) and (56) represent the assignments between the transportation mode and the products' states based on fractions. In other words, they fractionally distribute transportation capacities according to the products' states.

$$Sum\ of\ X = X1_t + X2_t + X3_t = 1 \quad (55)$$

$$Sum\ of\ Z = ZZ1_z + ZZ2_z = 1 \quad (56)$$

The following equations set the range of capacities for transportation modes at each processing route.

$$0 \leq TMAXC_t \leq 500{,}000 \quad (57)$$

$$0 \leq PMAXC_z \leq 50{,}000 \quad (58)$$

Model Parameters

Parameters such as the products' selling prices, demands, and availability of EFB were the same as in the previous model [21], while the other parameters are presented here. Tables A1–A5 in the Appendix A recorded the distances between the four stages of processing facilities as shown in the superstructure so that the model could determine the transportation costs. All these distances were obtained by using Google Maps. Furthermore, distances from j to l were tabulated according to the products' states. The data acquisition such as the operating cost factor and emission factor were acquired from [22] and [25] for each of the transportation modes. It was assumed that there was no emission from the pipeline transportation.

The production cost factors, conversion factors, and emission factors from productions were tabulated accordingly in Tables A6–A21 in the Appendix A. Particularly at l, depending on the states of products from j, separate tables have shown the related parameters clearly. Approximation of parameters was done due to the difficulties in obtaining real data for this model. The parameters were sufficient to prove the model's practicality, and they were independent of scales, configurations, feedstock conditions, etc.

4. Results and Discussions

The model formulation as shown above were implemented in GAMS Rev. 149 and solved by using the BARON Rev 8.1.1 in AMD A10-4600M APU processor. With the given parameters, the optimal value of overall net profit was obtained to be USD 1,561,106,613 per year, which could be gained by single ownership for all facilities in the supply chain. The model's statistics have shown that it has 66 blocks of equations, 55 blocks of variables, 6540 single equations, and 10,900 single variables, and it took 4 min to solve. Figure 4a shows the superstructure with processing routes (red dash arrows) and processing units (red dash lines) that would be eliminated prior to optimization, while Figure 4b shows the optimal one. The curve arrows represent option for selling of the products (i, k, m, o).

The superstructure optimization has eliminated processing routes and units. EFBs from collection point 1 (Johore) would be sent for pre-processing to all facilities except extraction 3 at the amounts of 3,147,894.737 tonnes per year. EFBs from collection point

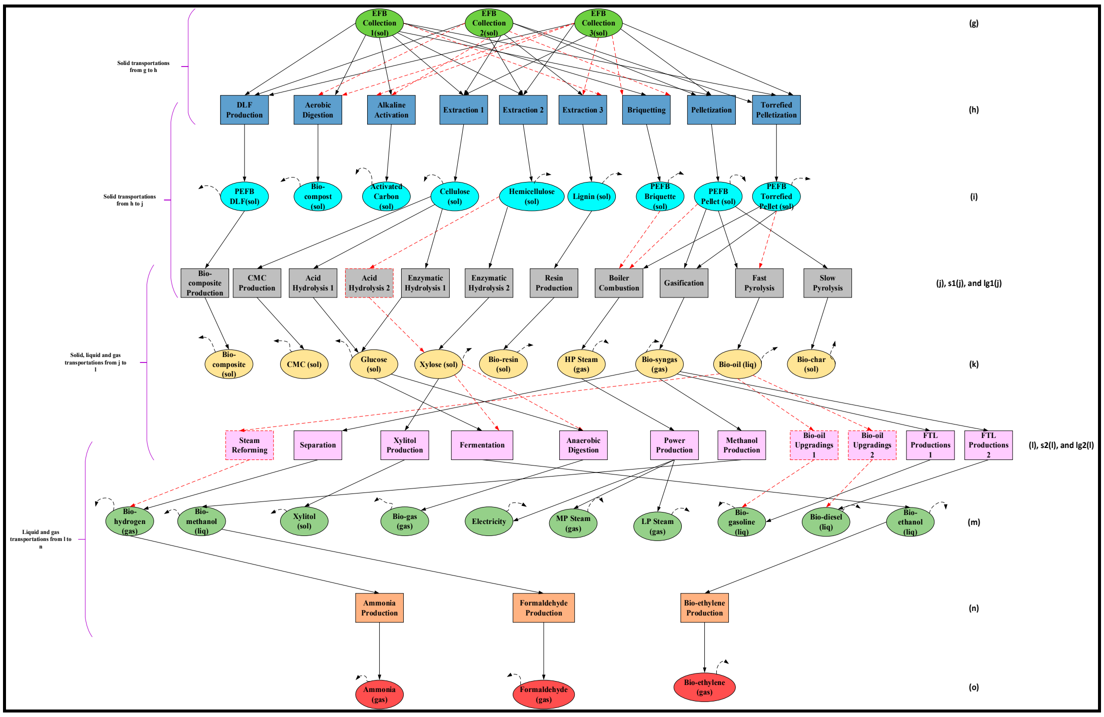
2 (Pahang) would be utilized at the amount of 2,717,543.860 tonnes per year and be sent to DLF production, extraction 1, extraction 2, extraction 3, pelletization, and torrefied pelletization. EFBs from collection point 3 (Perak) would be consumed at the amount of 2,447,368.421 tonnes per year in DLF production, extraction 1, extraction 2, pelletization, and torrefied pelletization. If the supplies of the EFBs at a single collection point were not sufficient, homogenous blending by using EFBs from other collection points would be conducted. To produce all the products, 8,373,235.36 tonnes per year of EFBs would be utilized at the cost of USD 6 per tonne. Table 4 shows optimal production levels of all products after optimal selections have been implemented.

Based on Figure 4a,b, from *i*, hemicellulose would no longer be sent to acid hydrolysis 2 but would only be consumed at enzymatic hydrolysis 2 to produce xylose. As a result, the processing route from hemicellulose to xylose through acid hydrolysis 2 has been eliminated in the optimal superstructure. Briquette and pellet were not sent to boiler combustion. Instead, the boiler combustion has only utilized torrefied pellet for producing HP steam. Fast pyrolysis has only one feed that came from pellet and is no longer using torrefied pellet as a feed.

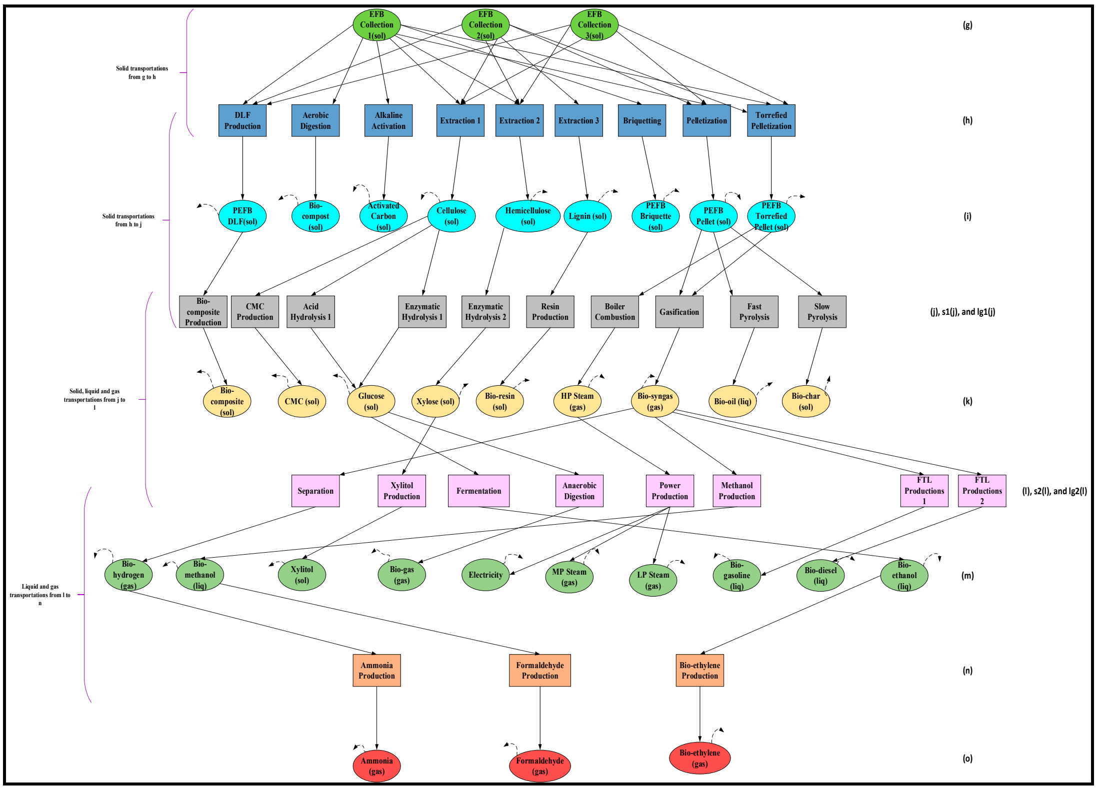
From *k*, the processing route from xylose to produce bio-gas through anaerobic digestion has been eliminated. Instead, there was only one optimal processing route to produce bio-gas through anaerobic digestion, which used portions of glucose. Xylose also was no longer an input to fermentation to produce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

Optimal results for transportation modes at each processing route and emissions from such transportation activities are tabulated in Tables 5–8. Emission values were negligible for transportations that used pipeline and transportations that involved very close distances between two processing facilities. Furthermore, the optimal results have assigned 97.9% of barges' capacities to serve for solid transportations between *g* and *h*, and the remaining capacities for transportations between *h* and *j*. For trains, 84.6% of their capacities have been used for transportations between *h* and *j*, and the remaining for solids transportations between *j* and *l*. For trucks, 86.1% of their capacities were utilized for solids transportations between *g* to *h*, and the remaining capacities were between *h* and *j*. For liquid and gaseous products, 97.2% of pipeline capacities were used for transportations from *j* to *l*, and the balances were assigned from *l* to *n*.

Tables 9–12 show the optimal results for productions of every processing facility with their respective emission levels. The optimal production rates in tonnes per year for all products have considered the constraint for which the annual demands must at least be met. In order to know what portion of the products needs to be sent for further processing, one could find the difference between the production rate and amounts to be sold directly to the customers.



(**a**)



(**b**)

Figure 4. (**a**) Optimization process for processing routes and processing unit. (**b**) Final superstructure of EFB supply chain with optimal processing routes.

Table 4. Optimal production level of products.

Product	Production (Tonnes per Year or MWh per Year)
DLF	543,314.563
Bio-compost	20,000.000
Activated carbon	95,000.000
Cellulose	290,500.000
Hemicellulose	186,503.475
Lignin	30,000.000
Briquette	186,000.000
Pellet	59,770.263
Torrefied pellet	129,749.841
Bio-composite	0.920
CMC	20,000.000
Glucose	277,200.544
Xylose	29,708.518
Bio-resin	10,000.000
HP steam	62,667.864
Bio-syngas	462,000.000
Bio-oil	41,587.981
Bio-char	3000.000
Bio-hydrogen	3581.311
Xylitol	0.002
Bio-ethanol	8924.511
Bio-gas	1295.000
Bio-methanol	0.300
Electricity	20.000
MP Steam	0.900
LP Steam	0.450
Bio-ethylene	140.000
Bio-diesel	348.809
Bio-gasoline	143.327
Ammonia	170.000
Formaldehyde	42.000

Table 5. Optimal results for transportations between EFB collection points, *g* and pre-processing facilities, *h*.

EFB Sources	Pre-Processing Facility	Amounts to be Transported (Tonnes per Year)	Optimal Mode of Transportation	Emission (Tonnes of CO_2 Equivalent per Year)
EFB collection 1	DLF production	489,473.684	Barge	1989.711
EFB collection 1	Aerobic digestion	21,052.632	Barge	-
EFB collection 1	Alkaline activation	190,000.000	Barge	592.800
EFB collection 1	Extraction 1	489,473.684	Barge	2364.158
EFB collection 1	Extraction 2	489,473.684	Barge	2364.158
EFB collection 1	Briquetting	489,473.684	Barge	1989.711
EFB collection 1	Pelletization	489,473.684	Barge	2107.184
EFB collection 1	Torrefied pelletization	489,473.684	Barge	1527.158
EFB collection 2	DLF production	489,473.684	Barge	1211.447

Table 5. *Cont.*

EFB Sources	Pre-Processing Facility	Amounts to be Transported (Tonnes per Year)	Optimal Mode of Transportation	Emission (Tonnes of CO_2 Equivalent per Year)
EFB collection 2	Extraction 1	489,473.684	Barge	1688.684
EFB collection 2	Extraction 2	489,473.684	Barge	1688.684
EFB collection 2	Extraction 3	270,175.439	Barge	932.105
EFB collection 2	Pelletization	489,473.684	Barge	1431.711
EFB collection 2	Torrefied pelletization	489,473.684	Barge	1644.632
EFB collection 3	DLF production	489,473.684	Barge	2011.737
EFB collection 3	Extraction 1	489,473.684	Barge	3568.263
EFB collection 3	Extraction 2	489,473.684	Barge	3568.263
EFB collection 3	Pelletization	489,473.684	Barge	2121.868
EFB collection 3	Torrefied pelletization	489,473.684	Barge	2540.368

Table 6. Optimal results for transportations between pre-processing facilities, h and main processing facilities, j.

Pre-Processing Facility and Product	Main Processing Facility	Amounts to Be Transported (Tonnes per Year)	Optimal Mode of Transportation	Emission (Tonnes of CO_2 Equivalent per Year)
DLF production and DLF	Bio-composite production	1.227	Train	8.905×10^{-4}
Extraction 1 and cellulose	CMC production	23,255.814	Truck	-
Extraction 1 and cellulose	Enzymatic hydrolysis 1	422,916.436	Train	2930.811
Extraction 1 and cellulose	Acid hydrolysis 1	291,222.487	Train	3498.165
Extraction 2 and hemicellulose	Enzymatic hydrolysis 2	33,759.683	Train	233.955
Pelletization and pellet	Gasification	422,916.436	Train	158.171
Pelletization and pellet	Fast pyrolysis	69,313.301	Truck	-
Pelletization and pellet	Slow pyrolysis	6000.000	Barge	31.050
Torrefied pelletization and torrefied pellet	Boiler combustion	209,127.960	Train	105.819
Torrefied pelletization and torrefied pellet	Gasification	219,122.199	Train	376.014

Table 7. Optimal results for transportations between main processing facilities, *j* and further processing 1 facilities, *l* (*s*2 and *l*2).

Main Processing Facility and Product	Further Processing 1 Facility	Amounts to Be Transported (Tonnes per Year)	Optimal Mode of Transportation	Emission (Tonnes of CO_2 Equivalent per Year)
Acid hydrolysis 1 and glucose	Anaerobic digestion	1850.000	Train	13.757
Enzymatic hydrolysis 2 and xylose	Xylitol production	0.003	Train	2.382×10^{-5}
Acid hydrolysis 1 and glucose	Fermentation	27,472.501	Pipeline	-
Boiler combustion and HP steam	Power production	66.667	Pipeline	-
Boiler combustion and HP steam	Power production for MP steam	2.571	Pipeline	-
Boiler combustion and HP steam	Power production for LP steam	1.286	Pipeline	-
Gasification and bio-syngas	Separation	8247.415	Pipeline	-
Gasification and bio-syngas	Methanol production	106.339	Pipeline	-
Gasification and bio-syngas	FTL Production 1	494.231	Pipeline	-
Gasification and bio-syngas	FTL Production 2	491.280	Pipeline	-

Table 8. Optimal results for transportations between further processing 1 facilities, *l* and further processing 2 facilities, *n*.

Further Processing 1 Facility and Product	Further Processing 2 Facility	Amounts to Be Transported (Tonnes per Year)	Optimal Mode of Transportation	Emission (Tonnes of CO_2 Equivalent per Year)
Separation and bio-hydrogen	Ammonia production	212.500	Pipeline	-
Fermentation and bio-ethanol	Bio-ethylene production	141.414	Pipeline	-
Methanol production and bio-methanol	Formaldehyde production	43.299	Pipeline	-

Table 9. Optimal results for productions at pre-processing facilities, *h*.

Processing Route	Production Rate (Tonnes per Year)	Amounts to Be Sold Directly (Tonnes per Year)	Emission (Tonnes of CO_2 Equivalent per Year)
Blended EFBs-DLF production-DLF	543,315.789	543,314.563	2227.595
Blended EFBs-aerobic digestion-bio-compost	20,000.000	20,000.000	400.000
Blended EFBs-alkaline activation-activated carbon	95,000.000	95,000.000	1672.000
Blended EFBs-extraction 1-cellulose	1,027,894.737	290,500.000	60,645.789
Blended EFBs-extraction 2-hemicellulose	220,263.158	186,503.475	14,317.105
Blended EFBs-extraction 3-lignin	40,526.316	30,000.000	2512.632
Blended EFBs-briquetting-briquette	186,000.000	186,000.000	9300.000
Blended EFBs-pelletization-pellet	139,108.301	59,770.263	27,900.000

Table 9. *Cont.*

Processing Route	Production Rate (Tonnes per Year)	Amounts to Be Sold Directly (Tonnes per Year)	Emission (Tonnes of CO_2 Equivalent per Year)
Blended EFBs-torrefied pelletization-torrefied pellet	558,000.000	129,749.841	44,919.000

Table 10. Optimal results for productions at main processing facilities, *j*.

Processing Route	Optimal Production Rate (Tonnes per Year)	Amounts to Be Sold Directly (Tonnes per Year)	Emission (Tonnes of CO_2 Equivalent per Year)
DLF-bio-composite production-bio-composite	0.920	0.920	6.883
Cellulose-CMC production-CMC	20,000.000	20,000.000	1940.000
Cellulose-acid hydrolysis 1-glucose	107,752.320	78,429.819	10,451.975
Cellulose-enzymatic hydrolysis 1-glucose	198,770.725	198,770.725	16,895.512
Hemicellulose-enzymatic hydrolysis 2-xylose	29,708.521	29,708.518	2436.099
Lignin-resin production-bio-resin	10,000.000	10,000.000	25,000.000
Torrefied pellet-boiler combustion-HP steam	62,738.388	62,667.864	47,053.791
Pellet-gasification-bio-syngas	296,041.505	286,702.241	201,308.223
Torrefied pellet-gasification-bio-syngas	175,297.759	175,297.759	119,202.476
Pellet-fast pyrolysis-bio-oil	41,587.981	41,587.981	49,181.949
Pellet-slow pyrolysis bio-char	3000.000	3000.000	1740.000

Table 11. Optimal results for productions at further processing 1 facilities, *l* (*s*2 and *l*2).

Processing Route	Optimal Production Rate (Tonnes per Year)	Amounts to Be Sold Directly (Tonnes or MWh per Year)	Emission (Tonnes of CO_2 Equivalent per Year)
Xylose-xylitol production-xylitol	0.002	0.002	1.640×10^{-4}
Xylose-anaerobic digestion-bio-gas	1295.000	1295.000	323.750
Xylose-fermentation-bio-ethanol	9065.925	8924.511	888.461
Bio-syngas-separation-bio-hydrogen	3793.811	3581.311	341.443
Bio-syngas-methanol production-methanol	43.599	0.300	3.619
Bio-syngas-FTL production 1-bio-gasoline	143.327	143.327	91.586
Bio-syngas-FTL production 2-bio-diesel	348.809	348.809	23.370
HP steam-power production-electricity	20.000	20.000	1.000
HP steam-power production-MP steam	0.900	0.900	0.045
HP steam-power production-LP steam	0.450	0.450	0.023

Table 12. Optimal results for productions at further processing 2 facilities, *n*.

Processing Route	Optimal Production Rate (Tonnes per Year)	Amounts to Be Sold (Tonnes per Year)	Emission (Tonnes of CO_2 Equivalent per Year)
Bio-hydrogen-ammonia production-ammonia	170.000	170.000	287.980
Bio-ethanol-bio-ethylene production-bio-ethylene	140.000	140.000	196.000
Bio-methanol-formaldehyde production-formaldehyde	42.000	42.000	3.486

Sensitivity Analysis

The optimal results that included the selections of optimal processing routes, transportation modes and decision variables which have been presented are subject to have differences depending on the parameters that were used. Uncertainties in economic and technological factors are among the influential issues in a deterministic modeling. Hence, investigations need to be done to find important parameters that could affect large variations to the optimal results. In this section, simultaneous considerations for multi-parameters were done. Even though a myriad of simultaneous perturbations is possible, the sensitivity analysis here has only considered ammonia's selling price, conversion factor and production cost factor for demonstration purposes. The changes in these parameters were carried out by classifying them into three scenarios as shown in Table 13. Both original selling price and production cost factor were increased until 50%, and the conversion factor was set until 0.95. The overall profits have shown non-linear patterns with the increased values of the three parameters. In the pursuit to find the most important parameter for the developed model, more thorough sensitivity analysis might be required.

Table 13. Sensitivity analysis for some parameters related to ammonia.

Scenario	Overall Profit
Original case (i) Selling price: USD 745/tonne (ii) Production cost factor: USD 377/tonne (iii) Conversion factor: 0.8	1,561,106,613
Scenario 1 (i) Selling price: USD 819.5/tonne (+10%) (ii) Production cost factor: USD 414.7/tonne (+10%) (iii) Conversion factor: 0.85	1,591,266,115
Scenario 2 (iv) Selling price: USD 968.5/tonne (+30%) (v) Production cost factor: USD 490.1/tonne (+30%) (vi) Conversion factor: 0.90	1,582,494,479
Scenario 3 (i) Selling price: USD 1117.5/tonne (+50%) (ii) Production cost factor: USD 564.5/tonne (+50%) (iii) Conversion factor: 0.95	1,615,100,296

5. Conclusions and Future Work

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

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

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Appendix A

Table A1. Distances for transporting EFB feedstock between g to h in km, $(DGH_{g,h})$.

EFB Sources Locations, g	Pre-Processing Facilities, h	Distance (km)
EFB Collection 1	Aerobic Digestion On Site	0
EFB Collection 1	DLF Production	271
EFB Collection 1	Extraction Plant 1	322
EFB Collection 1	Extraction Plant 2	322
EFB Collection 1	Extraction Plant 3	322
EFB Collection 1	Briquetting Plant	271
EFB Collection 1	Pelletization Mill	287
EFB Collection 1	Torrefied Pelletization Mill	208
EFB Collection 1	Alkaline Activation (Activated Carbon) Plant	208
EFB Collection 2	Aerobic Digestion On Site	0
EFB Collection 2	DLF Production	165
EFB Collection 2	Extraction Plant 1	230
EFB Collection 2	Extraction Plant 2	230
EFB Collection 2	Extraction Plant 3	230
EFB Collection 2	Briquetting Plant	165
EFB Collection 2	Pelletization Mill	195
EFB Collection 2	Torrefied Pelletization Mill	224
EFB Collection 2	Alkaline Activation (Activated Carbon) Plant	224

Table A1. *Cont.*

EFB Sources Locations, *g*	Pre-Processing Facilities, *h*	Distance (km)
EFB Collection 3	Aerobic Digestion On Site	0
EFB Collection 3	DLF Production	274
EFB Collection 3	Extraction Plant 1	486
EFB Collection 3	Extraction Plant 2	486
EFB Collection 3	Extraction Plant 3	486
EFB Collection 3	Briquetting Plant	274
EFB Collection 3	Pelletization Mill	289
EFB Collection 3	Torrefied Pelletization Mill	346
EFB Collection 3	Alkaline Activation (Activated Carbon) Plant	346

Table A2. Distances for transporting pre-processed feedstock between h and j in km, $(DHIJ_{h,j})$.

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

Table A3. Distances for transporting solid intermediate products 1 between j and $s2(l)$ in km, $(DJKL\_S_{j,s2})$.

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

Table A4. Distances for transporting liquid and gaseous intermediate products 1 between j and $lg2(l)$ in km, $(DJKL\_LG_{j,lg2})$.

Main Processing Facilities, *j*	Further Processing 1 Facilities, $lg2(l)$	Distance (km)
Boiler Combustion	Power Production	0
Boiler Combustion	MP Steam Production	0
Boiler Combustion	LP Steam Production	0
Acid Hydrolysis (1 and 2)	Fermentation Plant (1 and 2)	327
Enzymatic Hydrolysis (1 and 2)	Fermentation Plant (1 and 2)	65
Gasification	Separation Plant	0
Gasification	Methanol Production	404
Gasification	FTL Production (1 and 2)	19
Fast Pyrolysis	Bio-oil Upgrading (1 and 2)	94
Fast Pyrolysis	Steam Reforming Plant	0

Table A5. Distances for intermediate product 2 between $lg2(l)$ and n in km, $(DLMN_{lg2,n})$.

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

Table A6. Operating cost factor and emission factor for transportation mode.

Transportation Mode	Operating Cost Factor (USD per Tonne per km)	Emission Factor (Tonnes CO_2 Equivalent per Tonne per km)
Truck	0.1641	0.000062
Train	0.0333	0.000022
Barge	0.0136	0.000015
Pipeline	0.0500	-

Table A7. Approximated production cost factor at h in USD per tonne.

Biomass Type, g	Pre-Processing, h	Pre-Processed Product, i	USD/Tonne	Reference
Blended EFBs	DLF Production	Dry Long Fiber	85	[26]
Blended EFBs	Aerobic Digestion	Bio-compost	10	[27]
Blended EFBs	Alkaline Activation	Activated Carbon	144	[28]
Blended EFBs	Extraction 1	Cellulose	125	[29]
Blended EFBs	Extraction 2	Hemicellulose	130	[29]
Blended EFBs	Extraction 3	Lignin	135	[29]
Blended EFBs	Briquetting	Briquette	50	[30]
Blended EFBs	Pelletization	Pellet	60	[31]
Blended EFBs	Torrefied Pelletization	Torrefied Pellet	70	[31]

Table A8. Approximated conversion factor at h.

Biomass Type, g	Pre-Processing, h	Pre-Processed Product, i	Conversion Factor	Reference
Blended EFBs	DLF Production	Dry Long Fiber	0.37	[32]
Blended EFBs	Aerobic Digestion	Bio-compost	0.95	[33]
Blended EFBs	Alkaline Activation	Activated Carbon	0.50	[34]
Blended EFBs	Extraction 1	Cellulose	0.70	Assumed value based on hemicellulose and lignin conversion factor
Blended EFBs	Extraction 2	Hemicellulose	0.15	[35]
Blended EFBs	Extraction 3	Lignin	0.15	[36]
Blended EFBs	Briquetting	Briquette	0.38	[32]
Blended EFBs	Pelletization	Pellet	0.38	[32]
Blended EFBs	Torrefied Pelletization	Torrefied Pellet	0.38	[32]

Table A9. Approximated CO_2 emission factor at h.

Biomass Type, g	Pre-Processing, h	Pre-Processed Product, i	CO_2 Emission Factor (Tonnes CO_2 Equivalent/Tonnes of Product Produced)	Reference
Blended EFBs	DLF Production	Dry Long Fiber	0.0041	[37]
Blended EFBs	Aerobic Digestion	Bio-compost	0.0200	[38]
Blended EFBs	Alkaline Activation	Activated Carbon	0.0176	[39]
Blended EFBs	Extraction 1	Cellulose	0.0590	[29]
Blended EFBs	Extraction 2	Hemicellulose	0.0650	[29]

Table A9. *Cont.*

Biomass Type, *g*	Pre-Processing, *h*	Pre-Processed Product, *i*	CO_2 Emission Factor (Tonnes CO_2 Equivalent/Tonnes of Product Produced)	Reference
Blended EFBs	Extraction 3	Lignin	0.0620	Assumed value based on values for cellulose and hemicellulose
Blended EFBs	Briquetting	Briquette	0.0500	Assumed value
Blended EFBs	Pelletization	Pellet	0.0500	Assumed value
Blended EFBs	Torrefied Pelletization	Torrefied Pellet	0.0805	[40]

Table A10. Approximated production cost factor at *j* in USD per tonne.

Pre-Processed Feedstock, *i*	Main Processing, *j*	Intermediate Product 1, *k*	USD/Tonne	Reference
Dry Long Fiber	Bio-composite Production	Bio-composite	107.0	[41]
Cellulose	CMC Production	CMC	2500.0	[42]
Cellulose	Acid Hydrolysis 1	Glucose	73.4	[29]
Cellulose	Enzymatic Hydrolysis 1	Glucose	85.7	[29]
Hemicellulose	Acid Hydrolysis 2	Xylose	168.7	[29]
Hemicellulose	Enzymatic Hydrolysis 2	Xylose	83.1	[29]
Lignin	Resin Production	Bio-resin	1900.0	[43]
Briquette	Boiler Combustion	HP Steam	20.7	[44]
Pellet	Boiler Combustion	HP Steam	20.7	[44]
Pellet	Gasification	Bio-syngas	300.0	Assumed value based on 50% of Bio-syngas price
Pellet	Fast Pyrolysis	Bio-oil	1003	[45]
Pellet	Slow Pyrolysis	Bio-char	111.5	[46]
Torrefied Pellet	Boiler Combustion	HP Steam	20.7	[44]
Torrefied Pellet	Gasification	Bio-syngas	300.0	Assumed value based on 50% of Bio-syngas price
Torrefied Pellet	Fast Pyrolysis	Bio-oil	1003	[45]

Table A11. Approximated conversion factor at *j*.

Pre-Processed Feedstock, *i*	Main Processing, *j*	Intermediate Product 1, *k*	Conversion Factor	Reference
Dry Long Fiber	Bio-composite Production	Bio-composite	0.75	[47]
Cellulose	CMC Production	CMC	0.86	[48]
Cellulose	Acid Hydrolysis 1	Glucose	0.37	[29]
Cellulose	Enzymatic Hydrolysis 1	Glucose	0.47	[29]
Hemicellulose	Acid Hydrolysis 2	Xylose	0.91	[28]
Hemicellulose	Enzymatic Hydrolysis 2	Xylose	0.88	[29]
Lignin	Resin Production	Bio-resin	0.95	[49]
Briquette	Boiler Combustion	HP Steam	0.20	[50]
Pellet	Boiler Combustion	HP Steam	0.25	[50]
Pellet	Gasification	Bio-syngas	0.70	[51]
Pellet	Fast Pyrolysis	Bio-oil	0.60	[52]
Pellet	Slow Pyrolysis	Bio-char	0.50	[53]
Torrefied Pellet	Boiler Combustion	HP Steam	0.30	[50]
Torrefied Pellet	Gasification	Bio-syngas	0.80	[51]
Torrefied Pellet	Fast Pyrolysis	Bio-oil	0.60	[54]

Table A12. Approximated CO_2 emission factor at *j*.

Pre-Processed Feedstock, *i*	Main Processing, *j*	Intermediate Product 1, *k*	CO_2 Emission Factor (Tonnes CO_2 Equivalent/Tonnes of Product Produced)	Reference
Dry Long Fiber	Bio-composite Production	Bio-composite	7.481	[55]
Cellulose	CMC Production	CMC	0.097	Assumed value
Cellulose	Acid Hydrolysis 1	Glucose	0.097	[29]
Cellulose	Enzymatic Hydrolysis 1	Glucose	0.085	[29]
Hemicellulose	Acid Hydrolysis 2	Xylose	0.075	[29]
Hemicellulose	Enzymatic Hydrolysis 2	Xylose	0.082	[29]
Lignin	Resin Production	Bio-resin	2.500	[56]
Briquette	Boiler Combustion	HP Steam	0.750	[57]
Pellet	Boiler Combustion	HP Steam	0.750	Assumed value
Pellet	Gasification	Bio-syngas	0.680	[58]
Pellet	Fast Pyrolysis	Bio-oil	0.580	[52]
Pellet	Slow Pyrolysis	Bio-char	0.580	[52]
Torrefied Pellet	Boiler Combustion	HP Steam	0.750	Assumed value
Torrefied Pellet	Gasification	Bio-syngas	0.680	[58]
Torrefied Pellet	Fast Pyrolysis	Bio-oil	0.580	[52]

Table A13. Approximated production cost factor at *s*2(*l*) in USD per tonne.

Intermediate Product 1, *k*	Further Processing 1, *s*2(*l*)	Intermediate Product 2, *m*	USD/Tonne	Reference
Glucose	Anaerobic Digestion	Bio-gas	199.0	Assumed value for 50% less of the bio-gas price
Xylose	Anaerobic Digestion	Bio-gas	199.0	Assumed value for 50% less of the bio-gas price
Xylose	Xylitol Production	Xylitol	2100.0	Assumed value for 50% less of the xylitol price

Table A14. Approximated production cost factor at *lg*2(*l*) in USD per tonne or per MWh.

Intermediate Product 1, *k*	Further Processing 1, *lg*2(*l*)	Intermediate Product 2, *m*	USD/Tonne or MWh	Reference
Bio-oil	Steam Reforming	Bio-hydrogen	455.0	[59]
Bio-oil	Bio-oil Upgrading 1	Bio-gasoline	1089.0	[60]
Bio-oil	Bio-oil Upgrading 2	Bio-diesel	918.0	[60]
Glucose	Fermentation 1	Bio-ethanol	98.2	[29]
Xylose	Fermentation 2	Bio-ethanol	98.2	[29]
HP Steam	Power Production	Electricity	58.9/MWh	[50]

Table A14. *Cont.*

Intermediate Product 1, *k*	**Further Processing 1, *lg*2(*l*)**	**Intermediate Product 2, *m***	**USD/Tonne or MWh**	**Reference**
HP Steam	Power Production	MP Steam	12.0	Assumed valued based on the steam price
HP Steam	Power Production	LP Steam	7.0	Assumed valued based on the steam price
Bio-syngas	Methanol Production	Bio-methanol	83.6	[29]
Bio-syngas	Separation	Bio-hydrogen	112	[61]
Bio-syngas	FTL Productions 2	Bio-diesel	167.3	[29]
Bio-syngas	FTL Productions 1	Bio-gasoline	519.8	[60]

Table A15. Approximated conversion factor at *s*2(*l*).

Intermediate Product 1, *k*	**Further Processing 1, *s*2(*l*)**	**Intermediate Product 2, *m***	**Conversion Factor**	**Reference**
Glucose	Anaerobic Digestion	Bio-gas	0.70	[33]
Xylose	Anaerobic Digestion	Bio-gas	0.70	[33]
Xylose	Xylitol Production	Xylitol	0.70	[62]

Table A16. Approximated conversion factor at *lg*2(*l*).

Intermediate Product 1, *k*	**Further Processing 1, *lg*2(*l*)**	**Intermediate Product 2, *m***	**Conversion Factor**	**Reference**
Bio-oil	Steam Reforming	Bio-hydrogen	0.84	[63]
Bio-oil	Bio-oil Upgrading 1	Bio-gasoline	0.40	[64]
Bio-oil	Bio-oil Upgrading 2	Bio-diesel	0.20	[64]
Glucose	Fermentation 1	Bio-ethanol	0.33	[29]
Xylose	Fermentation 2	Bio-ethanol	0.33	[29]
HP Steam	Power Production	Electricity	0.30 MWh/tonne of steam	[65]
HP Steam	Power Production	MP Steam	0.35	[32]
HP Steam	Power Production	LP Steam	0.35	[32]
Bio-syngas	Methanol Production	Bio-methanol	0.41	[29]
Bio-syngas	Separation	Bio-hydrogen	0.46	[29]
Bio-syngas	FTL Productions 2	Bio-diesel	0.71	[51]
Bio-syngas	FTL Productions 1	Bio-gasoline	0.29	Assumed value from bio-diesel conversion factor

Table A17. Approximated CO_2 emission factor at $s2(l)$.

Intermediate Product 1, k	Further Processing 1, $s2(l)$	Intermediate Product 2, m	CO_2 Emission Factor (Tonnes CO_2 Equivalent/Tonnes of Product Produced)	Reference
Glucose	Anaerobic Digestion	Bio-gas	0.250	[66]
Xylose	Anaerobic Digestion	Bio-gas	0.250	[66]
Xylose	Xylitol Production	Xylitol	0.082	Assumed value based on value of xylose

Table A18. Approximated CO_2 emission factor at $lg2(l)$.

Intermediate Product 1, k	Further Processing 1, $lg2(l)$	Intermediate Product 2, m	CO_2 Emission Factor (Tonnes CO_2 Equivalent/Tonnes of Product Produced)	Reference
Bio-oil	Steam Reforming	Bio-hydrogen	16.930	[52]
Bio-oil	Bio-oil Upgrading 1	Bio-gasoline	13.000	[52]
Bio-oil	Bio-oil Upgrading 2	Bio-diesel	13.000	[52]
Glucose	Fermentation 1	Bio-ethanol	0.098	[29]
Xylose	Fermentation 2	Bio-ethanol	0.098	[29]
HP Steam	Power Production	Electricity	0.050	Assumed value
HP Steam	Power Production	MP Steam	0.050	Assumed value
HP Steam	Power Production	LP Steam	0.050	Assumed value
Bio-syngas	Methanol Production	Bio-methanol	0.083	[29]
Bio-syngas	Separation	Bio-hydrogen	0.090	[29]
Bio-syngas	FTL Productions 2	Bio-diesel	0.067	[29]
Bio-syngas	FTL Productions 1	Bio-gasoline	0.639	[29]

Table A19. Approximated production cost factor at n in USD per tonne.

Intermediate Product 2, m	Further Processing 2, n	Final Product, p	USD/Tonne	Reference
Bio-hydrogen	Ammonia Production	Ammonia	377	[67]
Bio-methanol	Formaldehyde Production	Formaldehyde	232	[68]
Bio-ethanol	Bio-ethylene Production	Bio-ethylene	1200	[46]

Table A20. Approximated conversion factor at n.

Intermediate Product 2, m	Further Processing 2, n	Final Product, p	Conversion Factor	Reference
Bio-hydrogen	Ammonia Production	Ammonia	0.80	[67]
Bio-methanol	Formaldehyde Production	Formaldehyde	0.97	[69]
Bio-ethanol	Bio-ethylene Production	Bio-ethylene	0.99	[46]

Table A21. Approximated CO_2 emission factor at n.

Intermediate Product 2, *m*	**Further Processing 2, *n***	**Final Product, *p***	**CO_2 Emission Factor (Tonnes CO_2 Equivalent/Tonnes of Product Produced)**	**Reference**
Bio-hydrogen	Ammonia Production	Ammonia	1.694	[70]
Bio-methanol	Formaldehyde Production	Formaldehyde	0.083	Assumed value
Bio-ethanol	Bio-ethylene Production	Bio-ethylene	1.400	[46]

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