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Integrated Biomass Supply Chain in Malaysia: A Sustainable Strategy

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As the social awareness has gradually increased, energy security has become an increasingly important consideration. Malaysia, a country that is blessed with extensive natural resources, has also recognised the need of exploring a reliable and sustainable energy source. However, due to several underlying bottlenecks, such as the traditional involvement of small medium enterprises (SMEs) in low-value utilisation of biomass, the development of the biomass industry in Malaysia is hampered. A novel mathematical model is developed to remove this inveterate barrier. In the model, vehicle capacity constraints are considered alongside with several environmental indicators, i.e., global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), photochemical ozone creation potential (POCP), nutrification potential (NP), aquatic toxicity potential (ATP), terrestrial toxicity potential (TTP), abiotic depletion potential (ADP), water footprint (WF) and land footprint (LF) to evaluate the sustainability performance of the supply chain. A case study in Johor state is opted to demonstrate the proposed model.

1. Introduction

After the first and second oil crisis held in 1973 and 1979, academicians and industry players have noticed the importance and necessity of having alternative and sustainable energy sources in future (Klemeš and Pierucci, 2008). Being one of the blessing country which endowed with extensive natural resources, Malaysia therefore poses an ideal and substantial potential for the bioenergy generation (Foo, 2015). Since biomass is considered as one of the significant renewable energy source, several energy policies and action plans have been implemented to encourage the use of biofuels for the power generation (e.g., Fifth Fuel Policy (EPU, 2001) and Renewable Energy Policy and Action Plan (EPU, 2011)).

In tandem with the Tenth Malaysia Plan, a vast number of research works have been conducted in order to boast the development of biomass supply chain industry in Malaysia. Lam et al. (2013) and Ng et al. (2013) had developed a two-stage optimisation model to synthesise a biomass supply chain in West Malaysia with the aim of maximising the annual profit while ensuring a minimal carbon emission. Besides, Tang et al. (2015) had introduced a game theory approach which able to determine the best strategy of palm biomass industries in Malaysia.

All the aforementioned works are admirable, but most of them do not consider the vehicle capacity constraints (weight and volume) in their model. However, these constraints are critical for biomass logistics management due to the low mass density nature of biomass. A more recent work had proved that using a linearised cost function when determining the transportation cost might lead to undesirable waste of investment (How et al., 2016). Only few works had considered these limitations. For instance, Iori and Martello (2005) solve the routing problem which associated with two- and three-dimensional loading constraint. Cheang et al. (2012) extend the traveling salesmen problem with last-in-first-out loading constraint. Moreover, How et al. (2016) had developed a graphical transportation decision-making tool which had accounted both weight and volume constraints. There is still very limited amount of research that had considered both vehicle constraints and sustainability performance simultaneously during the synthesis of biomass supply chain.

On the other hand, one of the key challenges for the biomass industries in Malaysia is the traditional involvement of small medium enterprises (SMEs) in low-value utilisation of biomass. Some biomass which contain high caloric value (e.g., rice husk) are commonly used as boiler feed for the co-generation for respective mills. Therefore, instead of converting these biomass into high-value products (e.g., bio-oil), these biomass are "locked" at the upstream process of the entire supply chain (MIGHT, 2013). Thus far, very few research had been conducted to resolve this inveterate bottleneck of the biomass industries in Malaysia.

In order to address the aforementioned issues, this paper proposes a novel mathematical model which considered vehicle constraints to develop a strategic solution that is economic feasible and environmentally benign for the biomass industries in Malaysia. It is worth to mention that, several environmental impact indicators which introduced by Heijungs et al. (1992) (i.e., global warming potential (GWP), acidification potential (AP), photochemical ozone creation potential (POCP), nutrification potential (NP), aquatic toxicity potential (ATP), terrestrial toxicity potential (TTP), abiotic depletion potential (ADP)), alongside with two environmental footprints (i.e., water footprint (WF) and land footprint (LF)) are used to evaluate the environmental performance of the biomass supply chain. In addition, an actual case study in Johor, Malaysia is used to illustrate the model.

2. Problem statement

The problem described in this paper aims to determine the optimal biomass allocation networks while optimising both economic and environmental performance of the supply chain simultaneously. It is formally stated as follow: given a set of biomass *r* supplied from a set of source points *i* is planned to be delivered to a set of processing hubs *j* via a set of transportation mode *m*. It is then converted into a set of intermediates *l* via a set of technologies *t* and valuable products *p* via a set of technologies *t'*. Finally, the products will be delivered to a set of demands *k*. On top of that, a set of pollutants *a* (e.g., CO_2) is emitted to the environment from the entire chain and will cause a set of environmental impacts *q* (e.g., GWP). The generic superstructure is shown in Figure 1.

3. Method

In this work, weighted method is used for the multiple objectives optimisation. In order to determine the relative priority scale for each objective in a more systematic way, Analytical Hierarchy Process (AHP) is introduced. In general, AHP is a theory of measurement through pairwise comparisons and relies on the expert's judgements to derive priority scales (Saaty, 2008). By using obtained priority scales, the formulated model can be optimised, with the aim of maximising the overall profit and minimising environmental impact simultaneously. Then, different sets of priority scale are used to test the sensitivity of the model.

4. Model formulation

The multi-echelon supply chain is modelled through Mixed Linear Programming (MILP). It is solved by using Lingo v14.0 (Lingo, 2015) with global solver. The description of the formulations, including constraint setting and objective function are presented in the subsections below.

4.1 Constraint setting

In this work, weight capacity limit of vehicle (Cap_m^{Weight}) and volume capacity limit of vehicle (Cap_m^{Volume}) are taken into account. Due to these constraints, the total amount of materials that can be delivered per vehicle per trip is limited. The required amount of trips, n^{Trip} can be determined as follow:

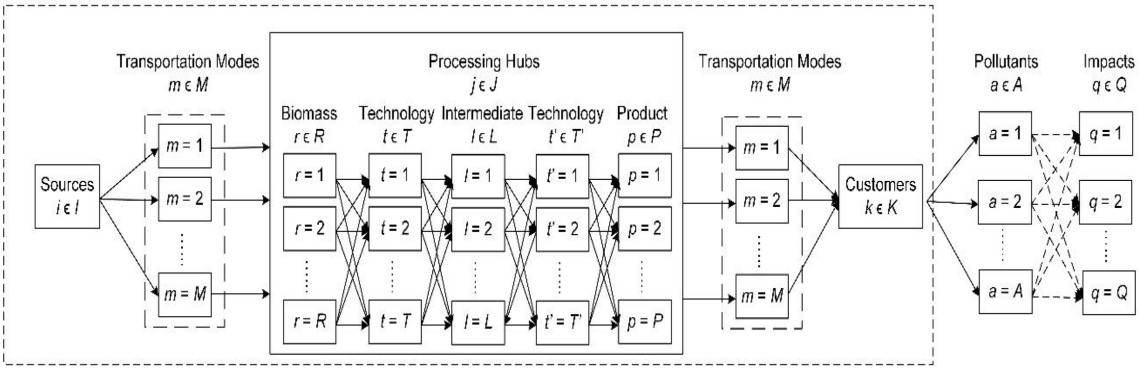

Figure 1: Generic structure of the proposed research problem.

$$n^{Trip} \geq \left\lceil \frac{F^{Weight}}{Cap_m^{Weight}} \right\rceil \qquad \forall m \in M \tag{1}$$

$$n^{Trip} \geq \left\lceil \frac{F^{Volume}}{Cap_m^{Volume}} \right\rceil \qquad \forall m \in M \tag{2}$$

where F^{Weight} [t/d] and F^{Volume} [m^3/d] refer to the weight-capacity and volume-capacity of materials (biomass *r* or products *p*) that are being delivered. Ceil functions ⌈…⌉ are used to round-up n^{Trip} to a positive integers since stopping in the mid-way is meaningless for the proposed problem. Please note that Eq(1) is used weight limiting problem (i.e., exceed weight limit before filling up the available space of vehicle) while Eq(2) is used for volume-limiting problem (i.e., exceed the volume limit before reaching the maximum weight limit).
Besides, Eq(3) is used as a hub determination constraint, where B_j refers to the binary variable which denotes the selection of hub *j*, $\sum_r \sum_i \sum_m F_{r,i,m,j}$ [t/d] refers to the total amount of biomass which delivered to hub *j*, while M refers to the maximum production limit in each hub:

$$\sum_r \sum_i \sum_m F_{r,i,m,j} \leq M \times B_j \qquad \forall j \in J \tag{3}$$

Eq(4) is used to ensure the total utilised amount of biomass is capped at the biomass availability, $F_{r,i}$ [t/d]:

$$\sum_m \sum_j F_{r,i,m,j} \leq F_{r,i} \qquad \forall i \in I,\ \forall r \in R \tag{4}$$

4.2 Economic evaluation

The evaluation of the economic performance considers three components, i.e., annual gross profit, C^{GP} [RM/y], annualised hub investment cost, C^{Inv_Hub} [RM/y], and annual transportation cost, C^{Tr} [RM/y]. The overall net profit, C^{NP} is defined as follow:

$$C^{NP} = C^{GP} - C^{Inv\_Hub} - C^{Tr} \tag{5}$$

The calculation for each term is adapted from How et al. (2016). C^{GP} is determined by revenue obtained from final products subtract the investment cost (i.e., biomass collection cost, operating cost and capital cost). C^{Inv_Hub} concerns of the fixed cost required to set up a processing hub. It encompassed of land cost and other construction expenses. C^{Tr} is obtained by summation of operating expenditures (based on distance travelled and number of trips required) and capital expenditure (based on the number of vehicle required).

4.3 Environmental evaluation

Instead of merely focusing on carbon emission, the proposed model also considers various forms of environmental impacts (e.g., water usage, acidification, etc.), EI_q [t-eq/y] in order to cover the full spectrum of environmental sustainability. It considers four components, i.e., environmental impact due to the pollutant emitted from the conversion process, $EI_q^{Process}$ [t-eq/y], potential environmental impact caused by products, EI_q^{Prod} [t-eq/y], environmental impact due to the energy consumption, EI_q^{Elec} [t-eq/y], and environmental impact due to transportation, EI_q^{Tr} [t-eq/y]. It is defined as follow:

$$EI_q = EI_q^{Process} + EI_q^{Prod} + EI_q^{Elec} + EI_q^{Tr} \qquad \forall q \in Q \tag{6}$$

$EI_q^{Process}$ can be determined by accounting the total potential environmental impacts (PEI) of each pollutant *a* which are emitted from the conversion process, F_a:

$$EI_q^{Process} = \sum_a (F_a \times \Psi_{a,q}) \qquad \forall q \in Q \tag{7}$$

where $\Psi_{a,q}$ refers to the PEI scores of pollutant *a* for impact category *q*. EI_q^{Prod} concerns the direct effect, $EI_q^{Prod\_Direct}$ (environmental-burdening) and indirect effect, $EI_q^{Prod\_Indirect}$ (environmental-unburdening such as substitution of fossil-based energy) of the products:

$$EI_q^{Prod} = EI_q^{Prod\_Direct} + EI_q^{Prod\_Indirect} \qquad \forall q \in Q \tag{8}$$

EI_q^{Elec} evaluates the environmental impact which attributed by imported energy, $Elec^{Imp}$ [kW] and self-generated bio-electricity, $Elec^{Gen}$ [kW]:

$$EI_q^{Elec} = (Elec^{Imp} - Elec^{Gen}) \times \Psi_q^{Fossil} \qquad \forall q \in Q \tag{9}$$

where Ψ_q^{Fossil} refers to the PEI score for fossil-based energy. Note that the negative sign for self-generation indicates the unburdening effect due to lower dependency on fossil-based energy. Lastly, EI_q^{Tr} determines the environmental impacts caused by fuel consumption during the transportation, F^{Fuel} [L/y]:

$$EI_q^{Tr} = F^{Fuel} \times \Psi_q^{Fossil} \tag{10}$$

Note that the PEI score for each component, is adapted from WAR GUI, build 1.0.17 (WAR GUI, 2011).

4.4 Multi-objective optimisation approach

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

$$\max\ \lambda^{SCM} = w^{Ec} \times \lambda^{Ec} + w^{En} \times \lambda^{En} \tag{11}$$

$$w^{Ec} + w^{En} = 1 \tag{12}$$

where λ^{Ec} and λ^{En} refer to the degree of satisfaction of the biomass supply chain based on economic performance and environmental performance; while w^{Ec} and w^{En} refer to the priority of economic sustainability and environmental sustainability based on AHP result.

$$\lambda^{Ec} = \frac{C^{NP} - C^{NP(L)}}{C^{NP(U)} - C^{NP(L)}} \tag{13}$$

λ^{Ec} concerns the net profit gained from supply chain where $C^{NP(U)}$ [RM/y] and $C^{NP(L)}$ [RM/y] refer to the maximal and minimal net profit that can be gained from the synthesised supply chain.

$$\lambda^{En} = \frac{EI_q^{(U)} - EI_q}{EI_q^{(U)} - EI_q^{(L)}} \qquad \forall q \in Q \tag{14}$$

λ^{En} indicates the degree of satisfaction of the environmental sustainability of the supply chain based on the results of the environmental indicators, where $EI_q^{(U)}$ [t-eq/y] and $EI_q^{(L)}$ [t-eq/y] refer to the upper limit and the lower limit of the environmental impact at category *q* caused by the entire supply chain.

5. Case study description

In this work, Johor state which endowed with diverse biomass resources is used as the case study. In this case study, four biomass sources, three types of biomass, three potential processing hubs, four types of trailers with different payload capacity (i.e., 5 t, 10 t, 20 t, 32 t), and four different technologies (combustion, fast pyrolysis, slow pyrolysis, gasification) alongside with two traditional practices (exportation, on-field burning) are considered. As already mentioned, currently, paddy straws (PS) are often disposed by on-field burning for the nutrient recycling purpose while rice husks (RH) are fed into the boiler for co-generation at rice mills. On the other hand, empty fruit bunches (EFB) are normally exported to overseas in its low value form. These practices result in low profit (due to low value usage) and high environmental impact (due to open fire). Therefore, the model is optimised to provide a sustainable strategy for the biomass utilisation, without compromising the benefit of each supply chain member. The geographical locations of the biomass source *i* and processing hub *j* are presented in Figure 2, while Figure 3 illustrates the traditional practice implemented in Malaysia.

6. Results and discussions

The proposed model is optimised by using a set of priority scale which obtained from AHP (i.e., w^{Ec} =67 %; w^{En} =33 %). Based on these priority scales, the model is expected to select a biomass utilisation pathway which contain higher economic potential. Figure 4 shows the optimised result which provides an annual profit which is 17.5 % higher (i.e., RM 1.49 x 10^7/y) and CO_2 emission which is 90 % lower (i.e., -622 t-CO_2/y) than the conventional practice. The general idea of the proposed strategy is to “unlock” valuable rice husk for downstream utilisation by using rice straw as a substituent for boiler feed. On the other hand, in order to generate higher revenue for the country, EFB is no longer exported in its low value form. Both rice husk and EFB are converted into high value products (i.e, biochar, bio-oil and syngas) via thermochemical conversion processes. It is worth mentioning that the production of biofuels is beneficial, as it can substitute the use of fossil-based fuels (lowering ADP). On the other hand, by recycling some of the produced bio-char back to the field will reduce the amount of imported fertiliser, resulting in lower cost for the millers. Table 1 tabulates the sustainability performance of the traditional practice and the proposed strategy. It shows that the proposed strategy provides higher degree of satisfactory. Sensitivity study is carried out by altering priority scale which used in the model and the results are tabulated as Figure 5. To illustrate, when w^{Ec} is set at 10 %, EFB is directly exported, RH is used as the feedstock for fast pyrolysis, while PS is used as boiler fuel. The result shows that the optimal solution obtained from the model is very sensitive to the priority scale input to the model. However, none of the solution supports the conventional practices which utilised rice husk as the boiler feed. This is probably due to the low boiler efficiency and the unattractive tariff established by the Malaysia government (Foo, 2015). On top of that, since the results are sensitive to the priority scale, collaborative stakeholder engagement is vital, in order to prevent mismatch expectation between stakeholders and reduce unnecessary investment. Similarly, the hub selection is also affected by the priority scale. Despite the model has significantly increase the overall sustainability performance of the biomass supply chain by removing the mentioned bottleneck, the high transportation expenses due to the nature of biomass (high moisture content and low density) is still a valid hurdle that have to be removed for the future development of biomass industries. On-site pre-treatment processes such as drying and densification (fiberizing, palletising, briquetting, packaging, etc.) are therefore vital. Moreover, joint-transportation planning can be carried out to further mitigate the extensive transportation cost (How et al., 2016). Last, but not least, international benchmarking is vital for the continuous improvement and sustainable development of an enterprise. By benchmarking the performance of Malaysia biomass industry against the neighbouring countries, the underlying problems of the biomass industry in Malaysia can be revealed effectively and efficiently.

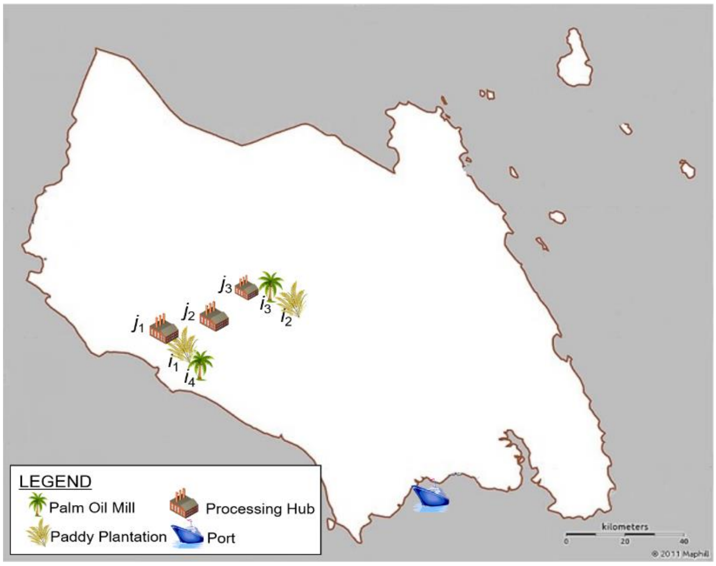

Figure 2: Geographical location (Maphill, 2013).

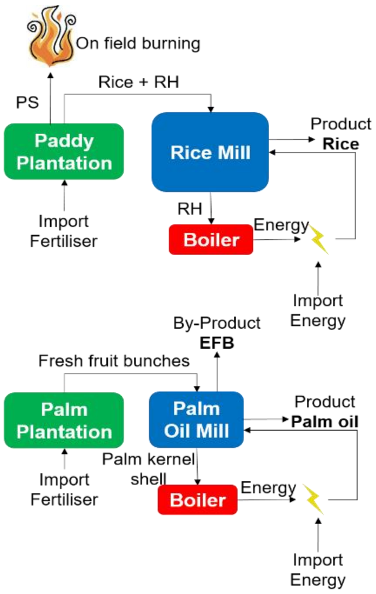

Figure 3: Conventional practice in Malaysia.

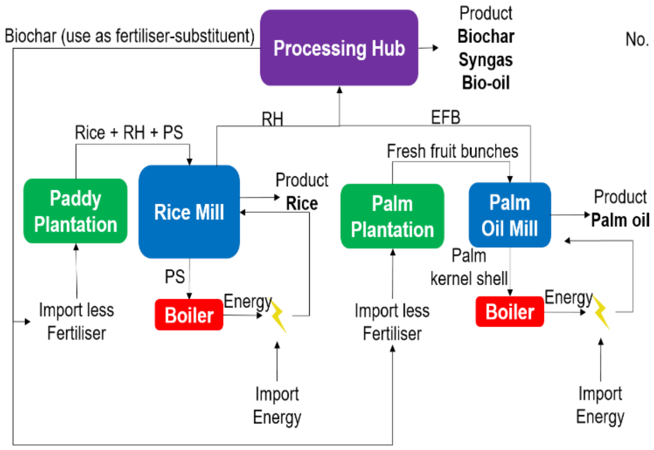

Figure 4: Proposed sustainable strategy.

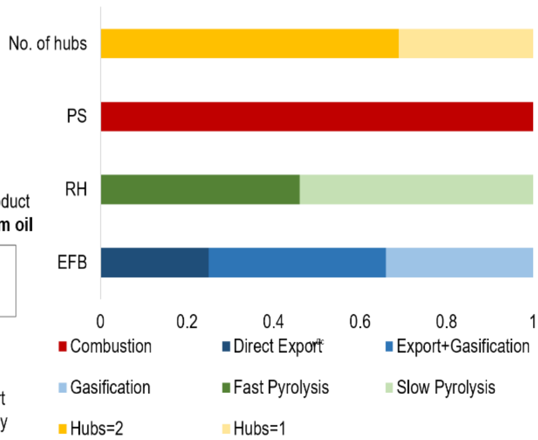

Figure 5: Effect of priority scale.

Table 1: Sustainability performances (all value in per y) of the biomass supply chain (w^{Ec} =67 %; w^{En} =33 %)

Practice	Hubs	C^{NP} [x10^8 RM]	GWP [kt-CO_2 eq]	AP [kt-SO_2 eq]	POCP [kt-C_2H_4 eq]	NP[kt-PO_4^{3-}]
Traditional	-	0.88	2.22	0.04	0.06	0.19
Proposed	j_1 and j_3	1.00	-10.1	-10.1	-1.08	3.52
Practice	**ATP [m^3/mg]**	**TTP [kt/mg]**	**ADP [kt-Kr/y]**	**WF [kt/y]**	**LF [m^2]**	**λ^{SCM}**
Traditional	0.008	9.72	-0.01	0.82	0 (no hubs used)	0.689
Proposed	1.09	-3.250	-0.07	4.24	40,000	0.878

7. Conclusion

This paper synthesised an integrated biomass supply chain with the consideration of both economic and environmental sustainability. The main contributions are stated below:
(1) A novel mathematical model which considers vehicle capacity constraint is proposed to generate a sustainable strategy for the development of biomass industries.
(2) The case study presented shows that the proposed model is applicable to provide improved strategy which increase the overall profit, while maintaining the sustainability of the biomass industry.
(3) Sensitivity study is conducted to analyse the effect of relative priority of each objective on the technology selection and optimal number of hubs.
(4) Several barriers that hampered the development of biomass industry in Malaysia is discussed and strategies are suggested in order to remove these barriers.
Future work will focus on extending this model to cover the social sustainability of the supply networks.

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