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Modelling and Optimization of Biomass Supply Chain for Bioenergy Production

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Abstract

Biomass utilization in the generation of bioenergy and biofuels is promoted as a sustainable solution to decarbonise the energy sector. Effective management of biomass supply chain is pivotal to successful deployment of this energy-rich resource in the power sector. Using a case study in Malaysia where biomass feedstock sourcing problem is prevalent, a biomass supply chain system was proposed. Three important terminals were identified, namely; i) biomass supply point (BSP), where raw biomass materials are collected, ii) biomass processing facility (BPF), as the collection hub cum centralized conversion centre, and iii) biomass demand centre (BDC), where the processed biomass meets the end-use sectors. A new modelling approach was proposed to optimize the new BPF location with the objective to minimize total road travelling distance between each terminal. The results were compared with the other commonly used methods, namely centre of gravity and fuzzy clustering. The positive contributions of the proposed model in minimizing the overall logistic cost and CO_2 emissions due to fuel consumption were discussed.

Keywords: Biomass, Palm Oil Mills, Bioenergy, Decarbonization, Supply Chain.

1 Introduction

Biomass is an energy resource derived from living matter such as field's crops and trees. Agricultural, forestry wastes and municipal solid wastes are also considered as biomass. Being in the tropical sun-belt, Southeast Asian countries enjoy a year-round sunlight which provides a favourable condition for agricultural activities. Global innovations in renewable energy technology and growing awareness on sustainable agricultural practice have prompted many countries in this region to adopt low carbon, bio-based energy production from their agricultural wastes. Among the common biomass feedstocks are bagasse, palm oil mill waste, and paddy husk.

In 2016, bioenergy power generation in this region tripled from 1.6 GW in 2000, to 7.2 GW (1). This promising progress is mostly contributed by Indonesia, Malaysia and Thailand who are experiencing rapid urbanization and industrialization. Malaysia for example, produces more than 103 million tons of biomass, including agricultural waste, forest residues and municipal waste (2). The agricultural waste represents 91% of the biomass amount, of which over 97% is derived from palm oil mill residues.

The land area used for oil palm plantation in Malaysia keeps growing, covering 5.8 million hectares of land in 2017 (3). The total amount of processed fresh fruit bunches (FFB) was about 101 million metric ton. After a series of processes which involves the removal of the oil fruits from the branches and oil extraction, about 72% of the FFB mass is left as biomass residues in the form of empty fruit bunches (EFB), mesocarp fibres (MF), palm kernel shells (PKS), and also palm oil mill effluents (POME).

These energy-rich biomass resources can be used to generate electricity, or converted to other marketable products such as bio-based chemicals, biofuels, animal feed, wood products and pellets. The estimated electricity generation potential of palm oil mill biomass comprised of EFB, PMF and PKS is between 2,400 – 7,460 MW (2, 4), while it is between 410 - 483 MW for biogas from POME (2, 5) (considering 7,200 operation hours of power plant).

In view of its high availability, biomass could play a central role in gearing up the share of renewable energy power generation. It can act as the base load for the national or regional grid, slowly taking over the role of coal power

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plants while decarbonizing the energy industry along the way. In order to capture this potential, a cost-effective biomass supply chain management is crucial. Establishing a centralized biomass collection center and conversion facility could be an essential component in the supply chain to reduce the processing cost and logistic cost.

1.1 Biomass Supply Chain System

Effective management of biomass supply chain is critically important to ensure bioenergy project viability and economic feasibility. Three important terminals along the supply chain have been identified, namely; i) biomass supply point (BSP), ii) biomass processing facility (BPF), and iii) biomass demand centre (BDC) or the market as shown in Figure 1.

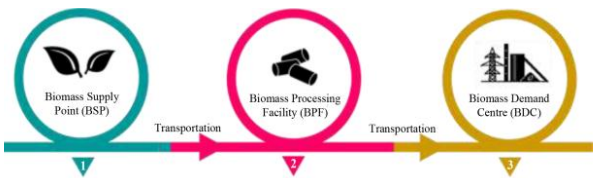

Figure 1: Supply chain in bioenergy production system.

Generally, BSP is where all the biomass is produced and will be collected from, such as the palm oil mills. Meanwhile, BPF serves as a collection hub and conversion facility. This is where the collected biomass will be stored and processed to improve its quality and durability before shipping. Finally, the processed biomass will be transported to BDC, where biomass is consumed by end-use sectors whether industrial, transport or residential. For industrial, it could be a power plant or a biorefinery. BDC could also function as a hub for national or international trade of biomass since there is a high demand for biomass pellet from South Korea, Japan & China, which may reach up to 16 million ton by 2020. International import and export of biomass will further promote diversification of its product portfolio and market competitiveness.

1.2 New Facility Location Optimization

The economic viability of bioenergy production system depends heavily on the cost of biomass feedstock supplies. Biomass sourced from agricultural industry in general is not expensive, the purchase price for raw EFB biomass for example, could be as low as 1.75 USD/tonne. However, the logistic cost to transport it from each BSP to BDC could be large and take a heavy toll on total biomass procurement cost. In a life cycle assessment of EFB consumption for green chemical production in Malaysia, Reeb *et al.* (2014) discovered that transportation cost caused substantial financial burdens, responsible for about 61% of the total delivered cost.

This is where BPF should come into play, by serving as a collection cum redistribution hub, hence ensuring efficient logistic chain and matching of demand and supply. The optimization of BPF location in between BSP and BDC is therefore critically important to minimize the logistic cost. Various mathematical approaches have been applied by past researchers to determine the strategic location of new facility. Many tried to resolve problems mostly related to the triple bottom line of sustainability; namely i) economy, through minimization of cost associated with transportation, storage and inventory, redistribution and disaster losses (6), ii) environment, through minimization of air pollution such as CO_2 emission (7), and iii) social, through maximization of social benefits such as job opportunities (8).

The center of gravity (COG) method is a well-established tool to find the geographical location a new facility which have to transport goods between the demand and supply points (9). This method ensures that the optimal location coordinates would minimize the required weighted travelling distances among them. In some cases, the method has to be modified such as implemented by Almetova *et al.* (2016) to cater unevenness in logistic flows in cargo network (10).

Furthermore, in order to a solve more complex, multi-objective, multi-echelon facility location problem, mixed-integer linear programming model is most commonly adopted (11–14). Some used fuzzy theory to manage situation of uncertain parameters (11, 15), while others used Fuzzy C Means (FCM) clustering algorithm as a complementary tool to assign geographical clustering of distribution points (16, 17) or to fine tune the facility location optimization result (18). In FCM method, an objective function called C-means functional is minimized through a fuzzified k-means clustering algorithm (19).

This study is a preliminary work to optimize BPF location provided that BSP and BDC locations are known and fixed, using a new modelling approach, which is the minimized least-square regression (LSR) method. This model enables simultaneous minimization of the road transportation distance between each terminal, with consideration of the number of trips required to transport all the biomass. The result will then be compared with the conventional COG and FCM methods. An empirical analysis was implemented via a case study in Perak, Malaysia, based on the current palm oil mill biomass availability data and existing road network.

2 Methodology

2.1 Facility Location Optimization Techniques

Three methods were used to determine the suitable location of BPF that reduces the overall logistic cost, which are; i) Centre of gravity (COG), ii) Fuzzy clustering or Fuzzy C Means (FCM) and iii) Least-square regression (LSR). The objective function is minimization of the total travelling distance between the terminals, on the premise that minimizing it will result in minimized total logistic cost and CO_2 emissions.

Unlike FCM which is suitable for multiple facility location problem, a geographical boundary needs to be pre-assigned prior to COG and LSR analysis. Three decision factors were considered: (a) state boundaries, (b) state/federal road transportation network, (c) biomass processing capacity. The distance from each BSP to BPF was set to be not more than 100 km. In addition, the biomass supply was assumed to always match the demand.

2.1.1 Centre of Gravity (COG)

The centre of gravity (COG) method indicates the ideal location in the grid-map that would ensure minimum weighted travelling distances. In biomass supply chain, raw biomass from each BSP will be transported to a new collection hub, which is the BPF. Therefore, the geographical coordinates of the existing *i*-BSP terminal (x_i, y_i), as well as the amount of biomass, w_i (ton/day) produced by each BSP were used as the weightage according to the following formula;

$$BPF\ location\ (x_j, y_j) = \left(\frac{\sum w x_i}{\sum w}, \frac{\sum w y_i}{\sum w}\right)$$

where x_i and y_i are the geographical coordinates of each BSP, (x_j, y_j) are the geographical coordinates of BPF and w is the amount of biomass (ton/day) transported from BSP to BPF.

2.2.2 Fuzzy Clustering or Fuzzy C Means (FCM)

Fuzzy C Means (FCM) clustering analysis was performed using a developed program in Fuzzy toolbox of Octave, which is available from Octave Software (GNU Octave, https://www.gnu.org/software/octave/). The input and output data were managed through a Microsoft Excel database. Given the data set X which includes geographical X and Y coordinates, the number of clusters 1 < c < N, the process is described as follows:

1.Input: keyed in the sample data set (two dimensional) contains geographical coordinates of x and y of each palm oil mill;

2.Fuzzy C Means algorithm call command – initialized the modelling process, number of clusters of c was given, which are two,

3.Output command: prompted the software to show the results

2.2.3 Least-Square Regression (LSR) Method

LSR basically calculates a line of best fit to a set of data pairs, minimizing the sum of squares of the vertical distances between the data points and the objective function. The required distance between each terminal may be represented in the form of following equation:

$$D^2 = (x_0 - x_1)^2 + (y_0 - y_1)^2$$

where D is the computed distance between each terminal. Using the Solver toolbox of Microsoft Excel software, the overall travelling distance, D_{total} between each terminal (BSP to BPF, and BPF to BDC) were minimized using the following equation;

$$D_{total} = \sum (D_{ij}\, t_{ij}) + (D_{jk} t_{jk})$$

where D_{ij} is the total travelling distance required to transport biomass from BSP to BPF, D_{jk} is the total travelling distance required to transport processed biomass from BPF to BDC, while t_{ij} and t_{jk} are the number of trips required to transport the biomass from each terminal.

Compared to COG method, this model enables simultaneous minimization of the road transportation distances between each terminal, with consideration of the number of trips required as the weightage. The model was solved using the Solver toolbox of Microsoft Excel by minimizing the set objective (D_{total}) and setting the variable cells as coordinates of BPF.

2.3 Mode of Transportation, Road Network, and Travelling Distance

Assuming that the biomass will be transported in a 20 tons-capacity truck (each supply will be fully loaded with 20 tons of raw biomass or less) the travelling distance will depend on the land transportation network. In reality, a highway that directly connects each terminal does not always exist. Therefore, the distance between two points is not linear, but depends on the actual existing road network. Given the coordinates of the potential BPF location optimized by each model, the road transportation distance was determined using information provided by Google Maps, then multiplied by the number of trips required to calculate the total travelling distance.

2.4 Logistic Cost and the Resultant CO_2 Emission

Assuming that the truck travels 40 mile per hour, the logistic cost was determined as the consolidated costs of three components which are truck driver wage, truck fuel cost and truck operation cost as listed below in Table 1;

Table 1: Logistic Cost

Component		Unit
Truck Driver Wage	18.35	USD/hr
Fuel Cost	2.1	USD/gallon
Truck Operation Cost	200	USD/hr

Estimations were made based on general case study on biomass transportation by 23 ton truck trailer (20) .

In addition, assuming the delivery truck travels 5 miles per gallon diesel, 2 x 10^{-3} metric tons of CO_2 would be emitted per each gallon (21).

2.5 Case Study Area

In order to locate and estimate the distance of each palm oil mills, a map was created by using Google Maps software. Perak, which is one of the major states of oil palm plantations in Peninsular Malaysia was selected as the region for our case study. In Perak, there are currently 29 operating palm oil mills with fresh fruit bunch (FFB) processing capacity of at least 20 tonne/hour as listed in Table 2, totalling to 1,494 ton of processed FFB/hour. In this study, the biomass of interest is EFB, which accounts for 22% of the FFB by weight.

The FFB processing capacity of each identified palm oil mill was used to estimate the amount of FFB processed daily using the following equation;

$$Processed\ FFB \left(\frac{ton}{day}\right) = FFB\ processing\ capacity\ \left(\frac{ton}{h}\right) x\ 12\ \left(\frac{h}{day}\right) x\ 0.9$$

The effective operating hour of each mill was assumed to be 12 h per day and there will be 0.1% losses of biomass during the palm oil production process.

For power generation, pretreatment of EFB is necessary to reduce its moisture content as well as to increase its energy density before firing. Considering that in BPF, the collected raw EFB will be transformed to EFB pellets which involves drying and pelleting could be produced daily was estimated based on the amount of processed FFB, which is 22% per tonne FFB on wet basis.

Table 2: List of palm oil mills and FFB processing capacity

No	Palm Oil Mill	FFB Processing Capacity (ton/hr)
1	Kilang Kelapa Sawit Lekir	100
2	Kilang Sawit Changkat Chermin	60
3	Pantai Remis Palm Oil Mill Sdn. Bhd.	60
4	KKS United Int. Enterprises (M) Bhd	100
5	Kilang Sawit Felcra Nasaruddin	40
6	Sri Intan Oil Palm Mill	60
7	KKS Peladang & Perusahaan Minyak	20
8	Awan Timur Palm Oil Mill	20
9	Topaz Emas Sdn Bhd	60
10	Temerloh Mill Sdn Bhd	45
11	Tian Siang Palm Oil Mill	120
12	Selaba Palm Oil Mill	40
13	KKS Ganda	20
14	Perak Agro Mills Sdn Bhd	30
15	KKS TRP	60
16	KKS Southern Perak	20
17	Felcra Processing & Engineering	30
18	Kilang Minyak Sawit Tanjung Tualang	40
19	Gabungan Perusahaan Minyak Langkap Oil Palm Sdn. Bhd.	60
20	KKS Perak Motor Co. Sdn Bhd	54
21	SYNN Palm Oil Sdn Bhd	60
22	Tian Siang Oil Mill	120
23	Central Palm Oil Mill	40
24	ST Palm Oil Mill	30
25	KKS Yee Lee Palm Oil Industries Sdn Bhd	60
26	KKS Tali Ayer (Hilltop Palm Oil)	20
27	KKS Chersonese	50
28	KKS Trolak	30
29	Elphil Palm Oil Mill	45

It was assumed that during the EFB pelletization process, only 70% of the mass will remain due to some losses of moisture content and biomass. Therefore, assuming the centralized BPF operates 6 days per week in every month, the amount of EFB pellets produced in a year would be;

$$EFB\ Pellets\ production\left(\frac{ton}{year}\right) = Processed\ FFB\ \left(\frac{ton}{day}\right)\ x\ 0.22\ x\ 0.7\ x\ 6\ x\ 12$$

In this study, the potential BDC is the existing thermal power station, which is also the largest operating coal power plant in Malaysia, Stesen Janakuasa Sultan Azlan Shah (SJSAS) situated near the . Currently, SJSAS only consumes pulverized bituminous & sub-bituminous coal mostly imported from Indonesia to fire up its boilers. Coal releases huge amount of pollutants upon combustion which include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) and particulate matter. Substituting a fraction of coal with biomass could reduce the amount of pollutants emissions significantly without much alteration needed in the power generation system.

3 Results & Discussion

3. 1 BPF Location Optimization

Figure 2 shows the locations of BSPs, BPFs and BDC. Since the palm oil mills (BSPs) are spread out far away from each other up to 200 km apart, it is simply not economical to have only one BPF centre. A single large scale biomass facility will require longer distances to transport biomass feedstock from multiple locations, thereby increases the logistic cost and overall cost of acquiring feedstock. The distance between each terminal should not be more than 100 km, and preferably less than 30 km because the transportation cost will be greatly affected by vicinity. Furthermore, assuming that the scale of each BPF should only be between 100,000- 500,000 metric ton/year, which are the common large scale pellet plants capacity in the United State, there should be at least two BPF centres (BPF1 and BPF2) to process EFB from all identified BSPs in the northern region and southern region of the Perak state.

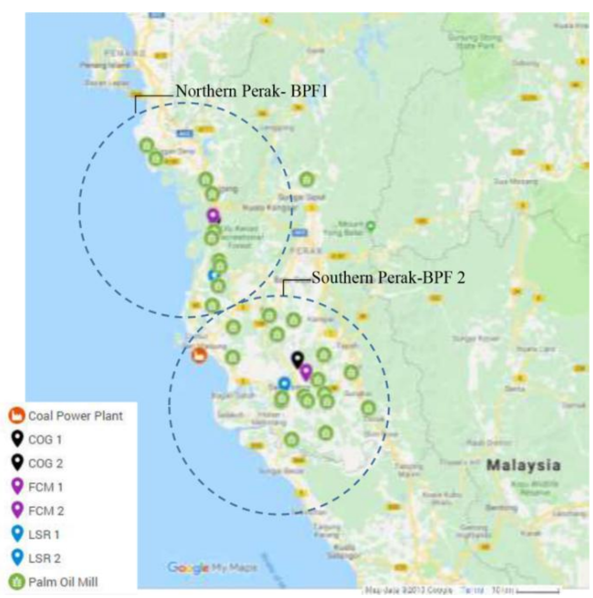

Figure 2: BPF location optimization for EFB supply from palm oil mills to a coal-biomass cofiring power plant.

Visually, the locations of BPFs as proposed by the three methods-COG, FCM and LSR are not far from each other, just around 5 to 10 km apart (except for the case of LSR-proposed location of BPF1, which is visibly far from the locations proposed by the other two models). However, when the number of trips was taken into account, there is a huge difference in the travelling distance along the biomass supply chain, as shown in Table 3. Comparative results show that the overall travelling distance is significantly minimized by the LSR method for both BPF1 and BPF2. As a consequence, a lot of savings can be gained in terms of logistic cost and CO_2 emission due to road transportation as shown in Table 4. By optimizing the travelling distance between two supply-and-demand points, which are BSP to BPF, followed by BPF to BDC, the proposed LSR method has outperformed the other two methods with the lowest total logistic cost and CO_2 emission of USD 46,570 and 3,170 kg CO_2 respectively. However, the purpose of this study is not to prove which method is the best, instead it serves to show that there exist multiple non-programming and handy approaches available to solve facility location problem. Each method has its own uniqueness and benefits as shown in Table 5. FCM clustering analysis could also work hand in hand with COG or LSR in a hybrid manner to solve a multiple facility location problem. FCM could be used to assign the geographical clustering first, then followed by COG or LSR to optimize the facility location. This sequential approach was also proposed by Esnaf and Küçükdeniz, 2009 (16). These methods could be applied when quick response is needed such as for emergency disaster relief distribution.

3.2 EFB Pellet Production

Table 6 shows the EFB production potential. A total of 3,179 ton of raw EFB can be collected and converted to EFB pellets amounted to 640,943 ton or 0.64 Mtpa per year. Currently, SJSAS power plant has 5 power generation units with total installed capacity of 4,100 MW_e and 9.5 Mtpa of annual coal consumption (22). Assuming that the plant exercise 3-5% biomass cofiring regime, and calorific value ratio of EFB pellet to coal is 0.76, the power plant would need about 0.38-0.63 Mtpa of biomass supply annually, which means that there will be a 100% local demand for the EFB pellets produced.

Table 3: The total land transportation distance necessary to transport the biomass from terminal-to-terminal.

Region	Method	Travelling distance between BSP to BPF, D_{ij} (km)	Travelling between BPF to BDC, D_{jk} (km)	Overall Travelling distance, D_{total} (km)
Northern Perak (BPF 1)	COG	2,287	3,245	5,531
	FC	2,390	3,182	5,572
	LSR	2,920	2,178	5,098
Southern Perak (BPF 2)	COG	4,013	4,594	8,607
	FC	3,615	4,930	8,545
	LSR	3,584	4,066	7,650

Table 4: Logistic cost and CO_2 emission due to road transportation.

Method	Total Fuel Consumption (gallon)	Total Logistic Cost (USD)	CO_2 emission (kg)
COG	1,757	51,647	3,516
FC	1,754	51,571	3,511
LSR	1,584	46,570	3,170

Table 5: Description of COG, FCM and LSR methods used in this study and lessons learned.

No	Method	Suitable Application	Parameters	Advantage(s) / Disadvantage(s)
1	Centre of gravity (COG)	Single/Multiple facility location problem	• x_i, y_i • w_i	• The simplest and well-established method to solve new facility location problem. • A precursor step is needed in order to define the geographical boundary prior to solve multiple facilities location problem.
2	Fuzzy C Means (FCM)	Multiple facility location problem	• x_i, y_i	• Can solve multiple facility location problem simultaneously and instantaneously. • Only applicable for multiple facility locations only (n facility must =>2) • Unmodified FCM clustering algorithm could not take into account the relative importance of BSP production capacity during location optimization.
3	Least-square regression (LSR)	Single/Multiple facility location problem	• D_{ij}, t_{ij} • D_{jk}, t_{jk}	• Can be used to solve multi-level distribution network. • A precursor step is needed in order to define the geographical boundary prior to solve multiple facilities location problem.

Table 6: Estimation of EFB pellet production based on FFB processing capacity of existing palm oil mills.

Biomass/Facility	Total FFB Processed (ton/day)	Total EFB production (ton/day)	Total EFB Pellets Production (ton/year)
BPF1	6,048	1,291	260,354
BPF2	8,791	1,888	380,589
Total	14,839	3,179	640,943

3.3 Limitation of Current Study

It should be noted that this paper is a preliminary study to test the performance of LSR method to solve a two-level distribution network–and compared it with the other conventional methods of facility location problem. Therefore, this study does not consider many other cost components such as inventory cost, labor cost, loading cost, and vehicle purchase and maintenance cost. Furthermore, it does not include risk assessment or sensitivity analysis on real problems such as seasonal biomass production therefore variety of biomass volume supply, demand changes, road condition, suitability of the proposed locations with the current city planning development, and proximity to water supply. In addition, the case study applied a conservative assumption that 100% of EFB collected will be converted to pellets, and that there is no other co-product of interest existed. As such, the results shown should be interpreted with caution and modification of the current work would be necessary to produce more accurate results.

4 Conclusion

This research has successfully applied LSR method to optimize BPF facility locations with the goal of minimizing the cost of supplying the required biomass to a power plant. Comparative results show that the transportation cost-performance can be improved significantly by the LSR method. LSR could outperform the other methods because it is the only method that take into consideration multi-level the travelling distance between each terminal. Moving forward, a more robust model optimization model and algorithm is needed to produce an integrated solution.

The analysis conducted in this study also sheds light on the expected volume of EFB supply and logistic cost, while the economic value derivable from the resources will require an establish market and relevant policies. For instance, mechanism for Competitive Generation Market, for multiple generators to trade with a single buyer; electricity wholesale market, where retailers can purchase energy from power plants; and Electricity Retail Market, where consumers can choose a retailer. Under a competition market, it is expected the EFB resources can play a competitive substitute or new resource to meet greener energy mix.

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