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Integrated GIS-AHP Optimization for Bioethanol from Oil Palm Biomass Supply Chain Network Design

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Integrated GIS-AHP network design optimization models via LP is proposed to solve the bi-objective biomass supply chain optimization problems inclusive of the management of cost-effective biomass resourcing spatial availability, optimal sites of biorefinery, and transportation network. The formulation is modeled through LP to minimize the logistic costs and GHG emissions. The case study focused on 78 palm oil plantations in Johor. The optimal biorefinery size and location were found by minimizing the total logistic cost by having less travel distance. The network design analysis feature in ArcMap is adopted in the analysis of the road transportation network by utilizing the '*OD cost matrix'* function. This spatial analysis is employed to calculate distances between supply nodes, biorefinery nodes, and demand nodes. There are about 8/78 resource locations and only a biorefinery has been selected with a total logistic 1.1 M USD/y and total GHG emissions about 0.128 Mt CO_2/y.

1. Introduction

Second-generation bioethanol, an advanced biofuel can be produced from renewable biologic wastes such as oil palm biomass. Malaysia, as a tropical country with an abundance of organic waste and biomass resources from the agricultural industry, has huge potential for biofuel development. Due to the rising concerns on climate issues, the ecological and energy transitions of fossil fuels to renewable transportation fuel become increasingly attractive. Bioethanol from oil palm biomass is one of the oxygenates blended to diesel to limit the diesel drawbacks such as mitigating emissions of hazardous materials including nitrogen dioxide (NO_x), sulphur oxide (SO_x), hydrocarbons (HC) containing aromatics likes pyrene, toluene, and benzene, carbon monoxide (CO), and particulate matter (PM) (Yilmaz et al., 2018). Biomass to biofuel is one of the pivotal roles of biomass for the decarbonisation of bioeconomy in Malaysia.

The conversion of biomass to biofuels from sustainable feedstock resourcing to commercializing a cleaner fuel is considered as supply chain network design. The cradle-to-grave supply chain network design. An efficient supply chain network design is decisive in practicing sustainable advanced biofuels development. Biomass to biofuel supply chain diversity includes biomass resourcing spatial availability, biorefinery localization, conversion process, and transportation (Samsatli et al., 2015) by optimizing economic and environmental impacts. Societal impact is important when determining the preferred biorefinery localization.

Oil palm frond (OPF) generally is disposed of in the plantation by burning on-site and composted as a soil amendment or organic fertilizer. This harmful practice creates environmental problems, and better alternatives need further intervention to ensure the sustainability of plantations and preserving ecosystems. OPF is the most abundant oil palm biomass produced in plantations, about 50 Mt/y (Mushtaq et al., 2015). OPF is a substrate for bioethanol production by direct conversion; physical, biochemical, and thermochemical processes (Razak et al., 2017). OPF contains higher carbohydrate (glucose) content, which is about 50-70 %

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of the free sugar (Abdullah et al., 2016), it has a high potential to be the carbon source for producing bioethanol. Besides the massive availability, OPF to bioethanol can circumvent the high-cost biomass disposal provide alternatives to environmental problems connected with disposal activities, and free conflict with sustainable food production (Da Silva et al., 2017). This initiative would reduce the GHG emissions footprint and spurring biomass economic metrics for higher value-added products significantly.

Specifically, the goal of this research is to emphasize a systematic approach for the optimal production planning and strategic decision making of biorefinery localization. To reap this potential, an integrated systematic approach combining Geographical Information System (GIS) with network design optimization (NDO) was developed. The best strategy to reduce this complexity is to adapt and adopt the integration of GIS and Analytic Hierarchy Process (AHP) through a spatial model approach via Linear Programming (LP). These approaches are conducted for the development of a systematic framework that is inclusive of the management of cost-effective biomass resourcing spatial availability, optimal sites of biorefinery, and transportation network analysis.

2. Methodology

A new systematic integrated GIS-AHP biomass to biofuel strategic and tactical planning optimization with spatial framework has been developed as schemed in Figure 1. This framework incorporates the use of several different tools ArcMap (ArcGIS) 10.3, Expert Choice v11, and GAMS 24.7.4 (CPLEX solver). This framework engaged sustainable spatial distribution and the strategic optimal biorefinery location. This implied OPF in Johor, Malaysia. Johor is the third-largest palm oil plantation in Malaysia with total land approximately 745,630 ha and about 13 % of total palm oil plantation in Malaysia (Sukiran et al., 2009). The accompanying sub-sections will include information on the main steps involved in the framework, including the biomass resourcing spatial availability assessment, optimal biorefinery localization, transportation network design, and optimization via LP.

2.1 Resource availability assessment

A list of OPF in palm oil plantation was obtained from SIRIM (2014). The biomass resource availability factors will be multiplied with the biomass production rates from palm oil plantation areas. The OPF availability is 7.5 t/ha.y (Loh, 2017). Malaysia's land use map for the year 2013 was extracted from MaCGDI (2018). For the oil plantation area, Johor, is computerized to retrieve the oil palm plantation layer in vector format that will be used in GIS. This oil plantation layer would be allocated to districts to obtain the availability of oil palm plantation biomass, which is the availability factor multiplied by the oil palm plantation area. About 78 active palm oil plantations were identified in Johor.

2.2 Network design

In this study, a bi-objective optimization for biofuel supply chain network design model via LP was proposed. This model integrates biomass resourcing spatial availability and optimal biorefinery localization, aiming at minimizing logistic cost and net carbon emissions score. ArcGIS network analysis provides an integrated network and spatial (location and attributes) analysis in solving supply chain network design.

This analysis adopts the origin-destination '*OD cost matrix'* solver to find and measure the least-cost pathways along with the network from multiple origins (resources) to multiple destinations (demands), and the target destination is evaluated by three attributes; (1) origin-destination pair, (2) travel times, and (3) travel distances. This novel strategic and tactical framework development extends prior research.

Akbarian-Saravi et al. (2020) developed an integrated bioethanol supply chain model to simultaneously address logistic and process production planning. Zhang et al. (2017) established the integration of GIS and biofuel supply chain network design for bioethanol from pulpwood. Martinkus et al. (2017) performed the integration of biogeophysical and social analysis network design for determining the optimal kerosene from wood biomass biorefinery sitting decisions. This network design envisages an integrated biofuel supply chain network design model that facilitates strategic decision making. To achieve this, an integrated GIS-AHP model is foreseen. GIS-AHP technique was used for suitability analysis in evaluating the optimal biorefinery location to ensure and maintain sustainable development (Ramya and Devadas 2019).

2.3 Optimal biorefinery localization

Optimal biorefinery localization is a key step in the production of economically viable and environmentally sustainable biorefinery localization. The localization of a biorefinery is primarily driven by biomass resourcing spatial availability, optimal biorefinery localization, and transportation network design (Mohd Idris et al., 2018). Network design was then evaluated by applying the most advanced technologies in the Multi-Criteria Decision Analysis (MCDA), a pairwise comparison-analytical hierarchy process (AHP) method by using the Expert

Choice v11 software. AHP is an MCDA methodology introduced by Saaty (2003). There are five attributes of optimal location such as travel distance, biomass resources capacity (supply), logistic cost, social matrix, and GHG emissions. Ioannou et al. (2018) concluded that GIS-AHP is a powerful tool for the determination of the optimal solution for any problem.

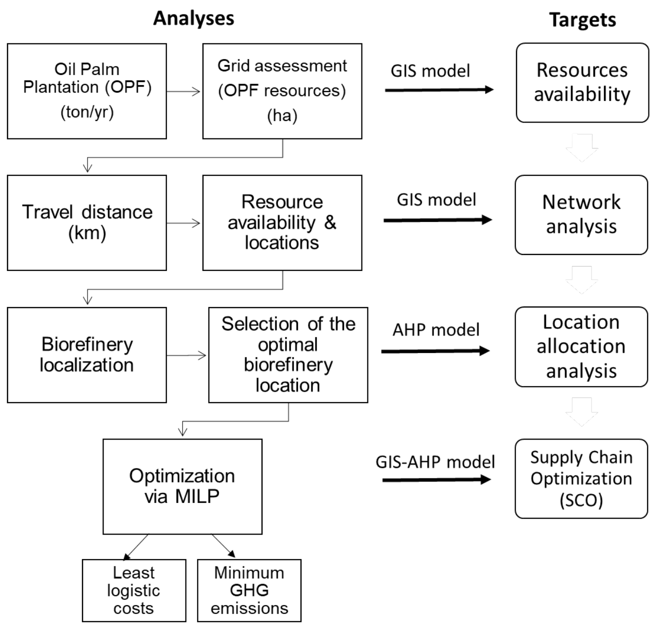

Figure 1: Supply chain optimization of biomass to biofuels

2.4 Model formulation

A supply chain network design optimization (NDO) models via LP that integrate GIS-AHP for sustainable OPF to bioethanol were developed. The objective function of this bi-objective LP model is minimizing the logistic cost and GHG emissions while determining the optimal biorefinery location. There are about 78 palm oil plantations as biomass resources and 8 potential biorefinery locations. The model constraints area is categorised into three groups. (1) biomass resource spatial availability, (2) demand constraint, and (3) biorefinery capacity constraints. The superstructure for this research is illustrated in Figure 3. Specifically, biomass supply i, biorefinery facility j, and demand center k. This cradle-to-grave network design includes three stages, which are biomass resources acquisition, conversion process, and product distribution.

As illustrated in Figure 2, OPF is harvested in palm oil plantations and pretreated in the biorefinery into small particles ready to be processed into biofuels. Pretreated biomass is then processed in the biorefinery facilities to be converted and upgraded to produce bioethanol. It is assumed that the conversion and upgrade of biofuels are carried out in the same facility (biorefinery) and then transported to the optimal biorefinery. Petronas Pengerang Integrated Complex (PIC) located in Pengerang, Johor which is 10 min away from biorefinery is the location of demand. The bioethanol will be blended with diesel in the PIC as a fuel additive. The final product is called a cleaner diesel. About 78 palm oil plantations and 8 possible biorefinery locations. The size of the biorefinery was determined according to the biomass spatial availability in t/y and bioethanol demand for blending with diesel in t/y.

3. Results and discussion

This work aims to determine a systematic economical-environmental biofuels network design optimization model. GIS-AHP integrated model with a logistic cost and emissions assessment was developed to determine the best candidate locations of biomass supply and centralized biorefinery. Potential locations of the centralized biorefinery are identified using a multi-criteria spatial analysis model that requires various land use and accessibility restrictions to assess the optimal locations. First, some vulnerable areas, such as forests and parks, wetlands, water sources, and urban areas are eliminated from the land use map. Second, the existing map that has been screened overlays with the transport buffers. Sahoo et al. (2016) claimed facility sites should be situated at an average distance of 3 km from the road networks to guarantee the connectivity and smooth flow for the transport of biomass.

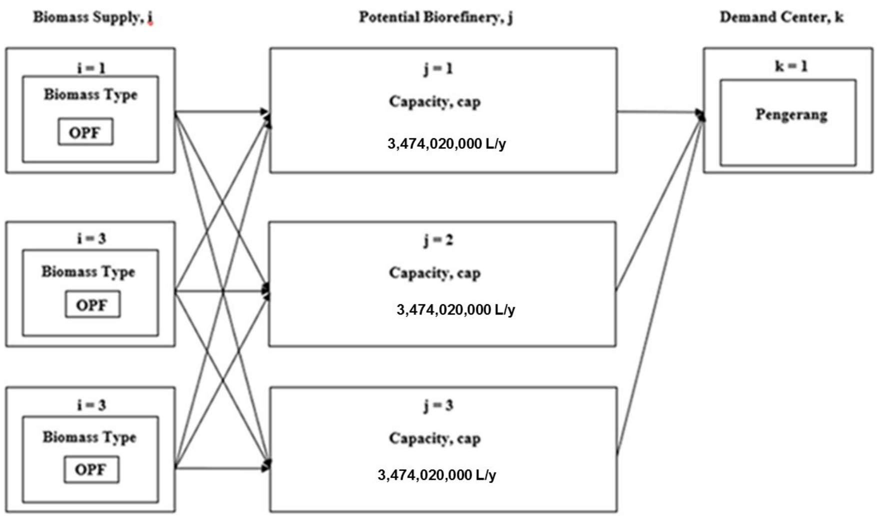

Figure 2: Biofuels supply chain network design

The economic objective function in this study is to determine the least logistic cost by minimizing the total cost (C^{total}) of the system. The total cost is made up of OPF biomass cost (C^{OPF}), transportation cost from oil palm plantation to demand center (C^{transp}), capital expenditure or CAPEX of biorefinery (C^{capex}) and operating expenditure or OPEX of biorefinery (C^{opex}) as described in the Eq(1):

$$Min\, C^{total} = C^{OPF} + C^{transp} + C^{Capex} + C^{Opex} \tag{1}$$

OPF biomass cost (C^{OPF}) is described by the multiplication of biomass's flow rate ($Fbiomass_{i,j}$) with the respective price of OPF biomass (C_{opf}) as given in Eq(2):

$$C^{OPF} = \sum_{i,j}(Fbiomass_{i,j} \times C_{opf}) \tag{2}$$

The cost of transportation from palm plantations to demand center (C^{transp}) is calculated by multiplying the flowrate of biomass ($Fbiomass_{i,j}$), flowrates of bio-alcohol ($Fethanol_{j,k}$) with the respective transportation distances ($Dist_{i,j}$ and $Bdist_{j,k}$) and respective transportation prices (P^{truck} and $P^{oil\ tanker}$). This can be defined as Eq(3):

$$C^{transp} = \sum_{i,j}(Fbiomass_{i,j} \times C_{truck} \times Dist_{i,j}) + \sum_{j,k}(Fethanol_{j,k} \times C_{tanker} \times Dist_{j,k}) \tag{3}$$

The capital expenditure or CAPEX in this model can be regarded as the investment to set up a new biorefinery. (C^{capex}) is calculated by multiplying the total CAPEX of biorefinery (T_{capex}), with the capacity unit of machine that is used to produce bio-alcohol ($CapUnit_j$). So, (C^{capex}) can be described as Eq(4):

$$C^{capex} = \sum_j(T_{capex} \times CapUnit_j) \tag{4}$$

The operating expenditure or OPEX is considered as the cost that is used for the operation of the biorefinery. The flowrate of butanol ($Fethanol_{j,k}$) times with the total OPEX of biorefinery (T_{opex}). So, it can be written as Eq(5):

$$C^{opex} = \sum_j(ethanol_{j,k} \times T_{opex}) \tag{5}$$

The second objective function of this model is is to mitigate the total emission of the system (E^{total}). The emissions resulting from the emissions of OPF biomass cultivation (E^{cultiv}), the emission from harvesting of OPF biomass ($E^{harvest}$), OPF biomass and bio-butanol transportation (E^{transp}) and last but not least from the technological emissions ($E^{technology}$). The minimization of total emissions can be represented as Eq(6):

$$Min\, E^{total} = E^{cultiv} + E^{harvest} + E^{transp} + E^{technology} \tag{6}$$

The emission from the cultivation of OPF biomass (E^{cultiv}) and the emission from harvesting of OPF biomass ($E^{harvest}$) is calculated by multiplying the respective emission factors with the biomass flowrate ($Fbiomass_{i,j}$). The two equations can be defined as Eq(7) and Eq(8):

$$E^{cultiv} \quad = \textstyle\sum_{i,j}(Ebiomass_{i,j} \times E_{copf}) \tag{7}$$

$$E^{harvest} \quad = \textstyle\sum_{i,j}(Ebiomass_{i,j} \times E_{hopf}) \tag{8}$$

There are two means of transportation involved in this supply chain system which is the truck and the oil tanker. So, transportation activity (E^{transp}) are described as the emissions from the truck (E^{truck}) and the oil tanker ($E^{oil\ tanker}$) can be represented as Eq(9)-(11):.

$$E^{transp} \quad = E^{truck} + E^{oil\ tanker} \tag{9}$$

$$E^{truck} \quad = \textstyle\sum_{i,j}(Ebiomass_{i,j} \times E_{truck} \times Dist_{i,j}) \tag{10}$$

$$E^{oil\ tanker} \quad = \textstyle\sum_{j,k}(Eethanol_{j,k} \times E_{tanker} \times Dist_{j,k}) \tag{11}$$

Eq(12) shows the technological emissions ($E^{technology}$) for the production of bio-alcohol is the flowrate of alcohol multiply with the emission factor of biomass to (E_{cf}).

$$E^{technology} \quad = \textstyle\sum_{j,k}(Eethanol_{j,k} \times E_{cf}) \tag{12}$$

The constraints take into account the major features of the biofuel supply chain, such as biomass availability, biorefinery capacities, and biofuel demand. Since it is not possible to harvest biomass feedstock above the available quantity, the flowrate of OPF biomass that is collected from oil palm plantation to the potential biorefinery ($\sum_j Fbiomass_{i,j}$) cannot exceed its biomass availability in oil palm plantation (A_i) as defined in Eq(13):

$$A_i \quad \geq \quad \textstyle\sum_j Fbiomass_{i,j} \tag{13}$$

The flowrate of bioethanol produced from OPF biomass at biorefinery ($\sum_k Fethanol_{j,k}$), should not exceed the maximum refinery capacity. The multiplication of (Cap and $Capunit_j$) is the capacity of biorefinery as shown in Eq(14):

$$Cap \times Capunit_j \quad > \quad \textstyle\sum_k Fethanol_{j,k} \tag{14}$$

The flowrate of bioethanol produced from OPF biomass at biorefinery ($\sum_k Fethanol_{j,k}$), should fulfill the demand. $demandPIC$ represents the demand at Pengerang Integrated Complex (PIC) as Eq(15):

$$demandPIC \quad \geq \quad \textstyle\sum_j Fethanol_{j,k} \tag{15}$$

As can be seen in Figure 3, Pantai Timor performs the best in three critical attributes; “the least logistic”, “the shortest travel distance from demand location”, and “the minimum GHG emissions. Pantai Timor is the strategic new biorefinery location with about 10 min to the demand with the least cost. Pantai Timor is also located near to the town, Bandar Penawar.

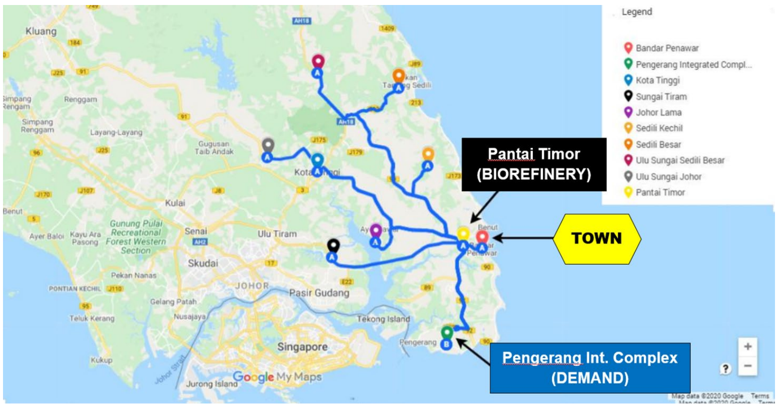

Figure 3: Biomass to biofuel supply chain network design in Johor, Malaysia (Google Map 2020).

Based on the integrated GIS-AHP network design optimization model via LP. Pantai Timor, Pengerang is the optimal new biorefinery location with a total logistic cost of approximately 11 M USD/y. The total demand capacity of biorefinery is 1.1 M L/y. 8 optimal resources locations are sufficient with total of 1.4 Mt/y of OPF to fulfil the demand in the biorefinery. The total GHG emissions is approximately 0.128 Mt CO_2/y.

4. Conclusions

A strategic network design LP optimization model has been developed successfully to evaluate the economic-environmental performance of the supply chain of OPB to bioethanol. The optimal biomass availability, optimal biorefinery capacity, optimal logistic cost, and total GHG emissions are the key to successful network design planning.

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