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Biorefinery Localization using Analytical Hierarchy Process

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A critical factor in producing economically viable and environmentally sustainable biomass to biofuels supply chains is a strategic biorefinery location. Sustainable biorefinery location is characterized by replacing fossil fuel with biofuels, enhancing cost-effectiveness, environmental issues mitigation, and stimulating socio-economic growth. The optimal biorefinery location selection depends on trade-offs between five different parameters: feedstock availability, distance, social measures, cost, and emissions. This paper aims to incorporate qualitative criteria and quantitative criteria using Analytic Hierarchy Process (AHP) in selecting the optimal biorefinery location. The model renders the AHP model to prioritize the optimal biorefinery location with the minimum cost and lower environmental impacts. Sensitivity analysis with continuous criteria weight at 20 % changes is performed to check the robustness of the optimal solution obtained from the AHP optimization model. A case study in Johor, Southern Malaysia, is adopted for this research assessment. Optimal biorefinery location at minimal cost and the lowest emissions is identified using Expert Choice v.11.5. The results indicate that the proposed AHP and sensitivity analysis decision-making model could be robustly used to select biorefinery locations with specified criteria. Conclusively, the systematic methodology presented can help facility planning authorities formulate viable location strategies for a biorefinery in volatile and complex global decision environments.

1. Introduction

The development of advanced biofuels using non-edible biomass as feedstock has garnered attention as promising renewable energy greenhouse gas mitigation and cleaner energy production. To achieve the successful innovation commercialization of second-generation biofuels, resource and technology management must be readily and cost-competitive with fossil-based fuel. Analysis and development of sustainable biomass to biofuels supply chains include biomass resource supply till biofuel production, known as the cradle to gate approach.

A critical factor in producing economically viable and environmentally sustainable biomass to biofuels supply chains is biorefinery localization. A strategic biorefinery site localization considers coordination of biomass feedstock availability, transportation network, and product delivery (demand) points (Razak et al., 2021). While economic constraints are the primary factor in site location, incorporating social measures within the location radius may further reduce the cost of constructing a biorefinery (Mohd Idris et al., 2018).

The novelty of this paper is the simultaneous combination of the sustainable spatial distribution using Geographic Information System (GIS) and optimal biorefinery site location by AHP. Many selection methods have been introduced, including stochastic programming (Hrabec et al., 2017), Fuzzy Linear Programming (Ilbahar Et Al., 2021), Fuzzy ANP-VIKOR (Wu et al., 2018), and the best-worst method (BWM) (Kheybari et al., 2019).

AHP is the most popular Multi-Criteria Decision Making (MCDM) technique because of its simplicity and structure. AHP evaluates and considering both the qualitative and quantitative factors for different configurations for multivariate situations (Saaty, 2008). A systematic AHP model determines the most economical biorefinery

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location to construct a commercial cellulosic butanol plant for renewable and clean diesel technology. Sensitivity analysis determines how a change of an objective would affect the alternatives. Sustainable biorefinery as one of the new bioeconomy is necessary to meet the biofuel-related policy goals and stimulate a low carbon economy.

This paper aims to incorporate qualitative and quantitative criteria by rendering AHP for biorefinery site locations, including the selection criteria and socio-economic metrics.

2. Analysis Hierarchical Process (AHP)

Analytical Hierarchy Process (AHP) optimization model ranks and selects the optimal biorefinery location. The total cost, including feedstock cost, logistic cost, CAPEX, and OPEX, are the key requisite for a sustainable biofuel supply chain. Feedstock, logistic, CAPEX, and OPEX costs are often considered in a total cost function minimized or subtracted from revenues, leading to total profit maximization (Jong et al., 2017).

The AHP includes constructing a hierarchical framework and pairwise comparison matrices, performing pairwise judgment, analyzing the comparison results, and ranking the best alternative that best matches the product targets (Saaty, 2003). This ranking and selection are based on priority eigenvector values and the pairwise five-point judgment consistency ratio. The pairwise comparison can be applied to determine which criteria are statistically significant (Mansor et al., 2013).

2.1 Development of AHP hierarchical framework

This study implied AHP and sensitivity analysis for the optimal biorefinery localization of oil palm fronds (OPF) to bioalcohol in Johor, Southern Malaysia. Johor is the third-largest palm oil plantation in Malaysia, with approximately 748,860 ha, and represents about 13 % of whole palm oil plantation in Malaysia. The OPF availability is 7.5 t/ha.y (Loh, 2017). Biorefinery can be developed as a new facility or integrated with an existing palm oil mill or co-located with an oil palm plantation. Based on biomass resourcing spatial availability analysis via ArcGIS, there are about 78 active oil palm plantations in Johor (Razak et al., 2021).

The shortlisted biorefinery locations are selected using the AHP model. Only one centralized biorefinery is chosen to supply the biofuels to the chosen demand centre. A centralized biorefinery is required to provide feedstock sustainably at a reasonable cost. Optimal biorefinery locations are identified using Expert Choice v.11.5. Figure 1 represents the systematic framework for determining the optimal biorefinery location using AHP and sensitivity analysis.

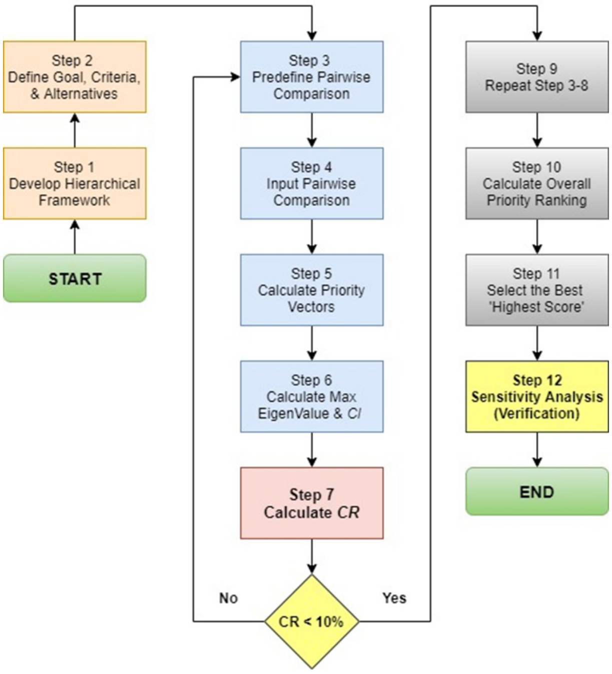

Figure 1: Systematic framework for determining the optimal biorefinery location using AHP sensitivity analysis

As the first stage of AHP, a four-level AHP framework is applied based on the criteria/attributes for biorefinery site localization are identified. In AHP hierarchy Level-1, the project goal is defined to select the optimal biorefinery location for the butanol from oil palm biomass production. Level-2 and Level-3 pinpoint the targeted five main criteria (cost, distance, feedstock, social measures, and emissions) and 15 sub-criteria (cost; feedstock cost, logistic cost, CAPEX, OPEX, logistic distance; supply to biorefinery, biorefinery to demand, biorefinery to the town, feedstock; availability, supply more than demand, emissions; transportation emissions, technology emissions, harvesting emissions, cultivating emissions, and social measures; near to the town).

In Level-4, one of the eight palm oil plantations in Johor (Pantai Timor, Sedili Kechil, Johor Lama, Sungai Tiram, Kota Tinggi, Sedili Besar, Ulu Sungai Sedili Besar, and Ulu Sungai Johor) is selected as the best alternative candidates. Connecting lines are constructed to link all the information within the framework indicating their relationship with each other. Figure 2 displays the overall hierarchical framework of the decision problem in selecting the optimal biorefinery site location.

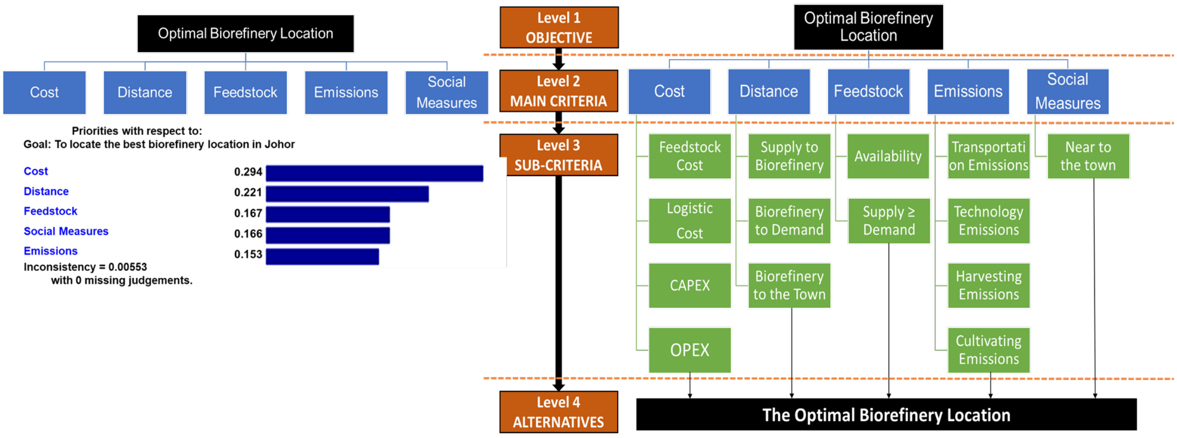

Figure 2: The hierarchical framework of the decision problem in selecting the optimal biorefinery location

2.2 Performing judgment using pairwise comparison

The second stage is to perform a pairwise comparison between the defined objective, criteria, and alternatives within the AHP framework developed in the earlier step. The pairwise comparison using AHP is used to decide on the relative importance between criteria concerning the objective and alternatives. The number of pairwise comparison evaluations depends on the number of criteria involved in the hierarchical framework. It is calculated using the *n(n-1)* rule, where *n* is the number of criteria. It is necessary to assign relative weights to the criteria, and then evaluate the overall alternatives to get the best solution that matches their needs in the main objective.

2.3 Synthesizing pairwise judgments and calculating eigenvector

The third stage in the AHP analysis is to synthesize all the pairwise comparison data into matrix form, normalizing the values within the matrix and calculating the priority vector. According to (Saaty and Ergu, 2015), the priority vector is obtained by constructing pairwise comparison matrices (size *n x n*) for each level, where *n* is the number of evaluation criteria considered. The eigenvalues can be obtained by calculating the eigenvector of comparison matrix *A*, as shown in Eq(1).

$$A = (a_{ij})_{n\,x\,n} = \begin{bmatrix} a_{11} & a_{12} & \dots a_{1n} \\ \vdots & 1 & \vdots \\ a_{n1} & a_{n2} & \dots 1 \end{bmatrix} \tag{1}$$

where $a_{ij} = k$ automatically implies that $a_{ij} = 1/k$ and $i, j = 1, \dots, n \; and \; i \neq j$. The a_{ij} is the importance scale and *n* is the number of criteria.

2.4 Performing consistency analysis using consistency ratio

For the fourth step, when many pairwise comparisons are performed, some inconsistencies may typically arise. Consistency Ratio (*CR*) plays a vital role in the hierarchical framework of AHP as *CR* can determine the consistency of pairwise comparison judgement. All comparisons between criteria and alternatives were analyzed to determine the data consistency for each criterion. The eigenvector can be applied to compute Consistency Index (*CI*) and *CR* and as depicted in Eq(2) and Eq(3) sequentially.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

$$R = \left(\frac{CI}{RI}\right) 100\ \% \tag{3}$$

where *n* is the criterion, λ_{max} is the maximal eigenvalue of the comparison matrix, *RI* is the Random Index which depending on *n* values. The consistency rate (*CR*) should be less than 10 %. If *CR* ≤ 10 %, the estimate is accepted (Saaty, 2008). In this study, the *CR* is 2%.

3. Results and Discussion

3.1 Optimal Biorefinery Location – Case Study in Johor, Southern Malaysia

Final AHP analysis, as shown in Figure 3, suggested that Pantai Timor is the optimal biorefinery location. Pantai Timor is selected to minimize the total logistic distances and costs for supplying customer demands. These best candidates are capable of satisfying the demand of the markets. The biorefinery capacity for bioalcohol annual demand is 1,017,830 t/y, and the OPF supply in total is 1,044,152.28 t/y. Pantai Timor is also the nearest city to the demand centre with about 15 km away. Pantai Timor is the optimal biorefinery location with the shortest distance from supply to demand.

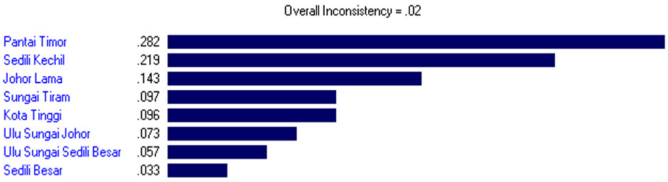

Figure 3: Overall results of the optimal biorefinery localization.

In the cost and emission scenario in Figure 4, Pantai Timor is the best candidate biorefinery location. Pantai Timor is the best candidate with the minimal total cost and the lowest emissions; 9 M USD/y, CO_2 emission, 0.128 t CO_2/y emission than other locations.

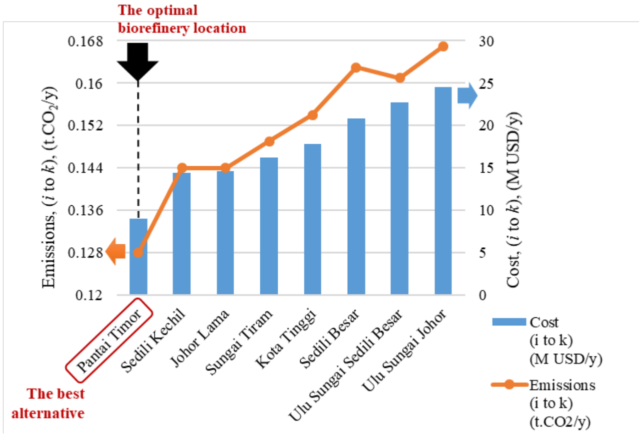

Figure 4: Pantai Timor is the optimal biorefinery location with low emissions and the least cost

Sustainability criteria in biorefinery locations make the biofuels market more attractive. Sustainable biorefinery location is characterized by replacing fossil fuel with biofuels, enhancing cost-effectiveness, environmental issues mitigation, and stimulating socio-economic growth. Biorefinery transportation network integrates a combination of rural and urban areas. The advantageous geographical position of biorefinery close to the town reinvigorates productive employment for residential. Biorefinery location should be located at an average distance of 3 km near the city to guarantee a seamless biofuel supply chain (Sahoo et al., 2016). Biomass feedstock supply, treatment facility (biorefinery), and demand centre increase the performance of the supply chain system (Permata et al., 2018).

3.2 Sensitivity Analysis

Sensitivity analysis is performed to check the robustness of the optimal solution obtained from AHP optimization. This analysis was executed using Expert Choice v.11.5. The stability of the pairwise evaluation can be observed by changing the five criteria: distance, feedstock, social measures, cost, and emissions. Sensitivity analysis is a *'Black Box Processes'* that can help validate which factors are essential and how changes in methods, models, or the values of variables affect the results.

In this study, the criteria weights change at 20 % is displayed in Figure 5. The primary vertical axis and secondary vertical axis represent scores of alternatives and the significance of criteria. The performance sensitivity analysis visualizes the priorities of the eight alternatives concerning five criteria. The results reveal a high degree of model stability (SuJeong and Álvaro Ramírez-Gómez, 2017). Pantai Timor scores the most flexible candidate under changes of criteria weights and represents the top-ranked for all eight alternatives (potential locations).

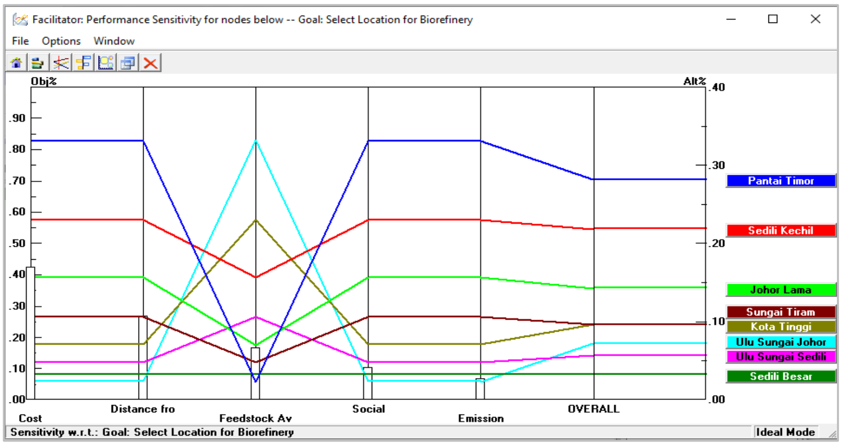

Figure 5: Performance sensitivity with 20 % changes

This analysis provides insight into the most critical criteria in selecting potential new biorefinery for bioalcohol from biomass production in Johor. The development of environmentally friendly and economically viable commercial-scale biorefinery is mainly associated with numerous technical, strategic, and sustainable challenges (Martinkus et al., 2019). Figure 6 visualizes the final result; Pantai Timor is the optimal biofuel location for a supply chain for this study.

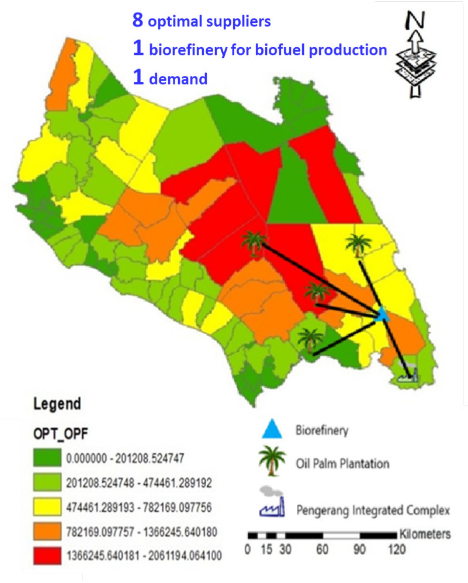

Figure 6: The optimal biorefinery location, Pantai Timor

4. Conclusions

This paper presents an operative AHP and sensitivity analysis approach that identifies the optimal biorefinery location for a case study in Johor, Southern Malaysia. First, the study decides the evaluation main criteria and sub-criteria; eight biorefinery as alternatives candidates are categorized into five criteria: feedstock, distance, social measures, cost, and emissions. The AHP optimization was performed to allocate the optimal biorefinery locations with the minimum total cost with lower environmental impacts. Sensitivity analysis with continuous criteria weight changes at 20 % is finally conducted to simulate the 'What-If' simulation exercise to predict the outcome of a decision given a specific range of variables and conclude the robustness of the AHP optimization results.

In the AHP model, 'Cost' and 'Distance' are the two top-ranking critical criteria for the performance assessment of biorefinery localization. The analysis of results concludes that the optimal biorefinery location has satisfied most of the criteria related to a sustainable bioeconomy. The proposed biorefinery location has the shortest distance from supply to demand, representing the lowest logistic cost. The lowest environmental impacts and the least cost are two primary criteria for determining a sustainable biorefinery location. Near to the town is the direct benefit to provide productive employment for residents. Therefore, the AHP and sensitivity analysis ascertain that this systematic methodology could be used for decision-making in biorefinery location assessment.

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