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MULTI-OBJECTIVE OPTIMIZATION MODEL FOR BIOENERGY SUPPLY CHAIN DISTRIBUTION

MODEL OPTIMASI MULTI-TUJUAN UNTUK DISTRIBUSI RANTAI PASOK BIOENERGI

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ABSTRAK

Menentukan rute distribusi yang optimal dalam mengatur jarak transportasi yang efisien merupakan tantangan dalam rantai pasokan bioenergi. Pengaturan distribusi yang memadai dapat meningkatkan distribusi dalam rantai pasokan bioenergi. Mengoptimalkan pengaturan distribusi dapat membantu mengurangi biaya transportasi, menghindari penundaan, dan meningkatkan efisiensi distribusi. Strategi distribusi yang optimal harus mempertimbangkan pemilihan rute yang meminimalkan jarak distribusi dari pusat-pusat pertanian ke pembangkit listrik. Penelitian ini bertujuan untuk menentukan lokasi titik pengumpulan dan rute distribusi yang optimal dalam pendistribusian rantai pasok bioenergi. Metode centre of gravity (COG) untuk menentukan lokasi titik pengumpulan. Penentuan rute distribusi optimal dengan kombinasi pendekatan ME-MCDM dan spasial Dijkstra. Hasil penelitian menunjukkan bahwa titik pusat di -60.53'42.6"LS dan 105.035'70.8" BT merupakan area pengumpulan biomassa untuk bioenergi yang sesuai. Metode yang kami usulkan yaitu kombinasi spasial Dijkstra dan pengambilan keputusan multikriteria (ME-MCDM) berdasarkan pertimbangan ahli mengenai solusi distribusi optimal bioenergi yang lebih logis dengan mempertimbangkan keberlanjutan memiliki TAV 1700,74 dengan P (V1, V5) = (V1, V2, V4, V5). Implikasi Manajerial bagi Perusahaan Penghasil Bioenergi dan Pemangku Kebijakan dari efisiensi operasional hingga pengurangan emisi karbon, model ini dapat membantu perusahaan untuk mengelola distribusi bioenergi dengan lebih baik dan berkontribusi pada keberlanjutan bisnis.

Kata kunci: distribusi bioenergi, optimasi model, pusat gravitasi (COG), ME-MCDM spasial dijkstra

ABSTRACT

Determining optimal distribution routes in managing efficient transportation distances is a challenge in the bioenergy supply chain. Adequate distribution arrangements can improve distribution in the bioenergy supply chain. Optimizing distribution arrangements can help reduce transportation costs, avoid delays, and improve distribution efficiency. The optimal distribution strategy must consider choosing routes that minimize distribution distances from agricultural centres to power plants. This study aimed to determine the location of collection points and optimal distribution routes in the distribution of the bioenergy supply chain. Centre of gravity (COG) method for locating collection centres. Determination of optimal distribution routes with a combination of ME-MCDM and spatial Dijkstra approaches. The results showed that the centre point at -60.53'42.6" S and 105.035'70.8" E is the biomass collection area for suitable bioenergy. Our proposed method of spatial combination of Dijkstra and multicriteria decision making (ME-MCDM) based on Expert considerations on a more logical bioenergy optimal distribution solution, taking into account sustainability, has TAV 1700,74 with P (V1, V5) = (V1, V2, V4, V5). Managerial Implications for Bioenergy-Producing Companies and Policy Stakeholders From operational efficiency to reducing carbon emissions, this model can help companies better manage their bioenergy distribution and contribute to business sustainability.

Keywords**:** bioenergy distribution, Centre of Gravity (COG), model optimisation, ME-MCDM Spatial Dijkstra

INTRODUCTION

Energy is crucial for the development of industry and trade (Chen, *et al*., 2023). Non-renewable fossil-base resources are expected to run out in the future (Afzal *et al*., 2023). Bioenergy is an alternative energy source to reduce the use of fossil fuels, which can produce greenhouse gas emissions resulting in global warming (Al-Hawari *et al*., 2022); (Duarah *et al*., 2022).

Bioenergy supply chains are complex and must be adaptive (De Meyer *et al*., 2014); (Seay and Badurdeen, 2014); (Yue *et al*., 2014). Involving many parties, including farmers, biomass producers, processing companies, governments, distributors, and end consumers (Razm *et al*., 2021); (Jilan *et al*., 2025). The development and efficiency of a robust bioenergy supply chain are crucial to ensuring the sustainability and success of bioenergy as an environmentally friendly energy alternative (Chia *et*

Coressponding Author

al., 2018). The Bioenergy Supply Chain includes: 1) Biomass sources, 2). Processing biomass into bioenergy; 3). Bioenergy production. After biomass is processed, the next step is to produce bioenergy according to the needs of bioethanol, biodiesel, biogas, or solid biomass such as briquettes and pellets; 4) Distribution and storage. The bioenergy produced is further distributed through transportation networks or stored for future use (Suyoko, Suyoko, & Asrol, 2024). 5)—consumption and users. The use of bioenergy is expected to reduce dependence on fossil fuels and decrease greenhouse gas emissions (Londoño-Pulgarin *et al*., 2021) a key aspect of the bioenergy supply chain in Prov. Banten exhibits significant development, particularly in the utilization of bioenergy as a renewable energy source. The development of energy crops for co-firing aims to establish a sustainable and optimal biomass supply chain from energy cropland to power plants.

The choice of collection center depends on the nature of the biomass collected, the availability of resources, and local needs (Moreno-Solazs *et al*., 2023). The center of gravity (COG) method involves spatial analysis, logistics, market, and demand studies with consultation and community participation based on economic analysis (Li *et al*., 2023); (Yasumiishi *et al*., 2020). The spatial analysis involves spatial data analysis and mapping to identify areas with a high biomass production potential (Krisnaningsih *et al*., 2022). Logistics Analysis involves modeling transportation networks and calculating distance, travel time, transportation costs, and transportation capacity to determine the optimal location for market study analysis, thereby reducing transportation costs and meeting demand efficiently efficiently (Wan *et al*., 2023). The economic analysis evaluates the financial feasibility of various potential locations. Cost factors are assessed to determine the site that provides the most optimal benefits (Peprah *et al*., 2023).

Optimizing distribution routes in the bioenergy supply chain is essential for efficient and cost-effective transportation of biomass feedstock, intermediate products, and bioenergy end products (Manikandan *et al*., 2023). The optimal distribution model aims to determine the most efficient path to transport these materials by considering the distance, mode of transportation, available infrastructure, and logistic constraints (Baghaei Daemi *et al*., 2022); (Kharrat *et al*., 2022); (Zhang *et al*., 2022).

Developing an optimal distribution route model requires expertise in supply chain management, logistics, transportation planning, and optimization techniques (Biuki *et al*., 2020); (Shahrier and Hasnat 2021). Collaborating with stakeholders from the bioenergy industry, including biomass suppliers, producers, transportation providers, and distribution centers, is imperative to gather insights and validate the model's effectiveness (Gao *et al*., 2019).

The Dijkstra Spatial Approach is one of the methods used for distribution optimization in the context of networks or distribution systems (Shahrier & Hasnat, 2021); (Dijkstra, 1959). This approach is based on Dijkstra's algorithm, originally used to find the shortest path between two points in a graph (Jason *et al*., 2023). The steps in Dijkstra's spatial approach to distribution optimization: 1) Identify the network to be optimized. 2). Determine weights for each side in the network based on relevant spatial factors. 3). Select the starting node on the network that will be used as the starting point for distribution optimization. 4). Initialization 5). Continue iterating until all nodes in the network have been fully exploited.

Multi-expert multi-criteria decision-making (ME-MCDM) is a valuable approach for complex decisions that require multiple perspectives and judgments (Massam, 1988). By involving several experts, this approach, combined with spatial Dijkstra, can produce more comprehensive choices and consider multiple relevant factors (Noor-E-Alam *et al*., 2011); (French, 2023).

Rice husk waste bioenergy still receives less attention. Technological limitations are still in the development stage and have not been widely applied in the industry. Rice waste has unique characteristics that impact the efficiency of energy conversion, and there is a notable lack of government regulations and policies in this sector compared to other energy sectors. Optimization methods are applied to improve the efficiency of bioenergy conversion and distribution.

This study aims to model the location of collection centers and optimal distribution routes in the bioenergy supply chain. By combining spatial Dijkstra optimization and multi-objective optimization techniques, we optimize bioenergy resource allocation, considering spatial relationships, transportation costs, and other relevant objectives.

MATERIAL AND METHODS

Haversine Methods

The Haversine formula is a fundamental equation in navigation, calculating the length of a great circle between two points on the globe's surface based on their longitude and latitude. Assuming that the Earth is perfectly round with a radius r of 6,367.45 km, and the locations of the 2 points at spherical coordinates (latitude and longitude) are γ 1.1 and ϕ2.2, respectively γ, then the Haversine formula in Equation (1).

$$d = 2r\, sin^{-1}\left(\sqrt{sin^2\left(\frac{\varphi_2-\varphi_1}{2}\right) + cos(\varphi_2)cos(\varphi_2)sin^2\left(\frac{\gamma_2-\gamma_2}{2}\right)}\right) \quad \ldots\ldots (1)$$

Information:

ϕ	=	Longitude
γ	=	Latitude
d	=	Distance
r	=	Earth
Radius	=	6371 km
1 degree	=	0.0174532925 radian

Centre of gravity (COG) Spatial

At this stage, using a spatial perspective, namely temporal-spatial congestion, danger zone risk, population density, capacity, and coordinates of each point (X, Y), and accommodation in Equation (2).

$$C_y = \frac{\sum_{i=1}^{n} d_{iy} W_i}{\sum_{i=1}^{n} W_i} \qquad C_y = \frac{\sum_{i=1}^{n} d_{iy} W_i}{\sum_{i=1}^{n} W_i} \quad \ldots\ldots (2)$$

Information:

Cx	=	Latitude coordinates
Cy	=	longitude coordinates
d	=	Distance
W	=	Capacity weight
i	=	1.2....., n
x	=	1.2,....., m
y	=	1.2,......., p

Based on the mathematical Equation, the formula (3) is obtained.

$$C_x \sum_{i=1}^{n} W_i = \sum_{i=1}^{n} d_{ix} W_i \quad C_y \sum_{i=1}^{n} W_i = \sum_{i=1}^{n} d_{iy} W_i \ .. (3)$$

Mx = modified latitude coordinates; My = modified longitude coordinates; d = distance; S= spatial perspective; i = 1, 2, ..., n; x = 1, 2, ..., m; y = 1, 2, ..., p is further converted into equation (4).

$$M_x = \frac{\sum_{i=1}^{n} d_{ix} S_i}{\sum_{i=1}^{n} S_i} \qquad M_y = \frac{\sum_{i=1}^{n} d_{iy} S_i}{\sum_{i=1}^{n} S_i} \ \ldots\ldots\ldots\ldots\ldots (4)$$

By adding a spatial perspective (Si) to the COG equation, assuming that the influence of capacity (W) is equivalent to S. The COG equation takes into account the spatial perspective on Equation (5):

$$M_x \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} d_{ix} S_i \quad M_y \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} d_{iy} S_i \ \ldots. (5)$$

The newly obtained COG equation is based on Equation (6):

$$C_x{}^* = \frac{C_x \sum W_i + M_x \sum S_i}{\sum W_i + \sum S_i} = \frac{\sum d_{ix} W_i + \sum d_i S_i}{\sum W_i + \sum S_i}$$
$$C_y{}^* = \frac{C_y \sum W_i + M_y \sum S_i}{\sum W_i + \sum S_i} = \frac{\sum d_{iy} W_i + \sum d_i S_i}{\sum W_i + \sum S_i} \quad \ldots\ldots. (6)$$

If all assumptions are met, then the COG equation becomes (7):

$$C_x{}^* = \frac{\sum_{i=1}^{n} d_{ix}(W_i + S_i)}{\sum_{i=1}^{n} (W_i + S_i)} \qquad C_y{}^* = \frac{\sum_{i=1}^{n} d_{iy}(W_i + S_i)}{\sum_{i=1}^{n} (W_i + S_i)} \ \ldots. (7)$$

Information:

C_x*	=	new latitude coordinates
C_y*	=	new longitude coordinates
d	=	Distance
S	=	spatial perspectives
i	=	1, 2, …, n
x	=	1, 2, …, m
y	=	1, 2, …, p

It utilizes the modified Dijkstra algorithm to determine the optimal route in physical distribution from COG to the consumer, incorporating a spatial perspective to select the optimal path. The routing problem with the shortest route is defined as follows: G(V, E) indicates the graph, where V is a set of vertices and E is a set of edges with source vertices ε E and target vertices ε E. In the case of depreciation, the path ρ = {e1, e2,..., er} is among all other paths that satisfy the property ρ starting at s and ending at t. Using the classic Dijkstra, the way from the source node V1 to the target node Vn in Equation (8):

$$P_i = (V_i, V_n) = (V_1, V_2, \ldots, V_n) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Information:

P	=	routes
V	=	vertex or nodes
i	=	1, 2, …, n

Non-Numeric Multi-criteria Decision-Making (MCDM)

Step 1	:	A set of I experts as individual decision makers, E = {E1, E2, ..., Ei}. Each h ε E decision maker gives a non-numerical preference.
Step 2	:	Define an alternate route A = {A1, A2, ..., Ar} that goes from one node to another connected node (i, j) in a graph network where each alternate route is an e A
Step 3	:	Define a conflicting criterion C={C1, C2, ..., Cj}. When we choose C1, this has the opposite effect of C2, Cj, or C2 and Cn
Step 4	:	For each conflicting criterion, its importance is determined. We are advised based on the preferences of experts as decision-makers ε E. The average is taken from experts' perceptions if there is a noticeable difference
Step 5	:	The importance of the criteria c ε C is then negative based on the scale used. This method employs a five-dimensional scale, as determined in Equation (9).

$$eg(W_k) = W_q - k + 1 \ldots\ldots\ldots.. (9)$$

k: Index; q: Total scale

Step 6 : Create an assessment matrix for alternatives, an ε A and criteria c ε C based on the number of experts h ε E

Step 7 : Define aggregations based on the criteria specified in Equation (10).

$$V_{ij} = min[Neg(W_{ak}) vV_{ij}(ak)] \ldots \quad (10)$$

k = 1, 2, ..., l

Step 8 : Weighting expert aggregations according to Equation (11)

$$Q_k = Int\left[1 + \left(k^*((q-1)/i)\right)\right] \;..\; (11)$$

q = number of grading scales; i = number of experts. Then convert the Qk result to the importance criterion level, for example, five = Very High (VH).

Step 9 : To get the alternative value of Ai, we collect the results of expert aggregation using Equation (12).

$$A_i = f\left(1 + \left(k^*((\quad)q-1)/i\right)\right) \;..\; (12)$$

j = 1, 2, ..., m; bj is the most significant sequence of expert assessments

Step 10 : Calculating alternative values (AV): AV is the alternative weight obtained from alternative aggregations and criteria on the non-numerical ME-MCDM method with Equation (13).

$$AV = (AV_1, AV_2, \ldots, AV_r) \ldots\ldots.. \quad (13)$$

r = number of alternatives

We modify each alternate value into a number using a five-dimensional scale. Any alternate value AV = {AV1, AV2, ..., AVr} is converted, e.g., Very High (VH) = 1. If you use a different scale, conversions are adjusted to that scale.

Multicriteria Spatial Dijkstra

Therefore, in addition to distance (Di), we added alternative (AVi) and spatial perspective weight (SPWi). The SPW value can also be obtained by grouping distances (Fitness) to predict it, by assigning a multiplier to the algorithm. Route selection is based on the shortest distance and Total Alternative Value (TAVi). The space referred to in this SPW is part of the TAV formulation. While the AV value contains coordinates (X, Y, and Z) and altitude, we refer to it as a spatial perspective (Figure 1).

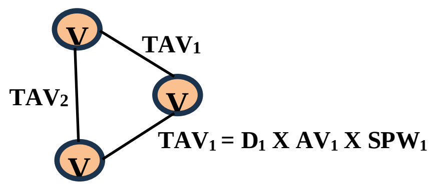


Figure 1. Single graph network using spatial Dijkstra

Based in Figure 1, the alternative route is P1(V1, V3) = (V1, V2, V3) or P2(V1, V3) = (V1, V3). The steps for the spatial Dijkstra algorithm are as follows :

Step 1 : Give each node a label. The node is filled with numbers, while the path is filled with distance D = {D1, D2, ... Di} from one node to the next.

Step 2 : Define spatial perspective variables. Spatial perspective in this method is determined by the spatial variable S = {S1, S2, ..., Sv}.

Step 3 : Calculate the ratio of each spatial variable. Determine the percentage of each spatial variable R= {R1, R2, ..., Rv} where the total rate equals 100%. Give each spatial variable a value in each path (node to nearest node) SV = {SV1, SV2, ..., SVj).

Step 4 : Calculate each path's spatial perspective weight (SPWi) in Equation (14).

$$SPW_i = \sum R_{iv} \times SV_{ij} \ldots\ldots\ldots\ldots\ldots \quad (14)$$

SPW = weight of spatial perspective; R = ratio of each spatial variable; SV = spatial variable; spatial variables; i = 1, 2, ..., n; j = 1, 2, ..., m; v = 1, 2, ..., p.

Step 5 : Change the SPW value of each path to maintain consistency with the Dijkstra algorithm; we convert the SPW value accordingly. This conversion aims to obtain the optimal value from a spatial perspective on Equation (15).

$$SPW_i = 10 - SPW_i \ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

SPW = Spatial perspective weighting; i = 1, 2, ..., n.

Step 6 : Calculate the total alternate values in Equation (16)

$$TAV_i = D_i \times AV_i \times SPW_i \ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

TAV = total alternative value; D = distance; i = 1, 2, ..., n. The result of this new method is not always the shortest route. However, the accumulation of TAV is the smallest. Then this is determined as the most optimal alternative route (Rs) with the smallest number of TAV values, where

$$TAV = \{TAV_1, TAV_2, \ldots, TAV_i\}$$

Rs = min ∑ TAV; Rs = the most optimal route; TAV = total alternative value

Research Framework

A general framework for developing a multi-objective optimization model for bioenergy distribution is shown in Figure 2. Model validation and refinement: Validate model results with real-world data and compare them with existing bioenergy distribution systems

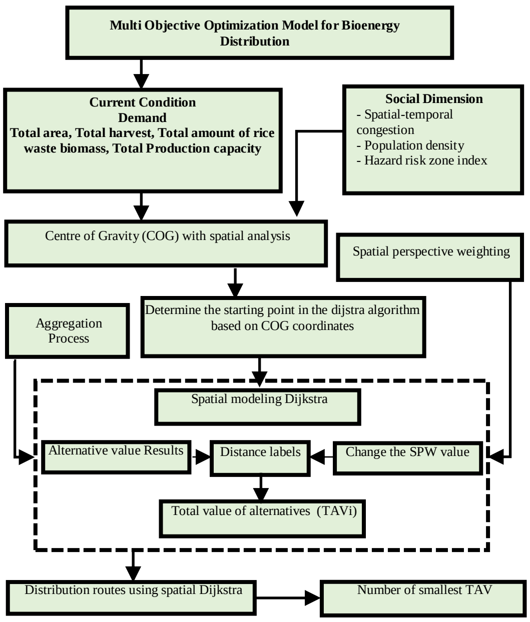


Figure 2. The research framework

RESULTS AND DISCUSSIONS

Bioenergy Supply Chain Based on Rice Plant Waste

The supply chain begins with collecting rice plant waste from rice fields or processing plants. The bioenergy supply chain model, based on rice plant waste, is illustrated in Figure 3.

A multi-criteria optimization model for bioenergy distribution is a mathematical approach to selecting the best solution for allocating limited resources to different objectives or criteria. Typical goals in bioenergy distribution include economic efficiency, environmental sustainability, supply reliability, and social equity. In this model, each purpose is represented by a variable to be optimized, while the constraints are defined by limitations in the mathematical model.

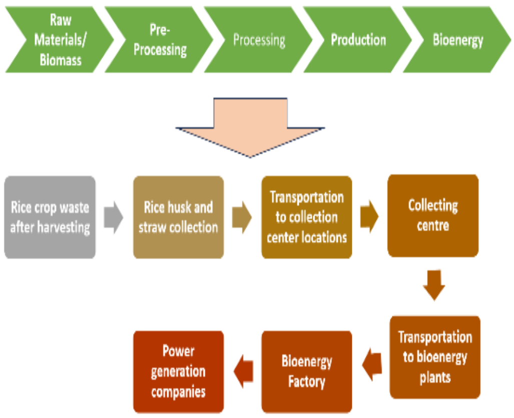


Figure 3. Bioenergy supply chain model

Data Collection and Analysis

Spatial data processing using data sets from Badan Pusat Statistik, BPS Banten, Indonesia, and field research with direct observation.direct observation to determine distribution channels in detail using the Google Maps application. Collection centers in the bioenergy supply chain depend on factors such as the availability of raw materials, transportation infrastructure, and market needs. Location Coordinates in Table 1. The geographic information system overlays maps with *grid techniques* to determine the sample coordinates in Figure 4.

Distance determination is based on the distance values in the Google Maps application, as shown in Table 2—a 5-point implementation from source V1 to destination V5 with nine alternate paths in Figure 5.

We use spatial perspective to determine the most optimal distribution route. We include the spatial aspect, that is, the temporal-spatial bottleneck. Temporal and spatial congestion is observed during the period of 9:00-24:00; congestion often occurs in the Pandeglang area (V2) to Labuhan (V3) and from Bojonegoro (V4) to Suralaya (V5).

Table 1. Location coordinates

Symbol	Location	Role	Latitude (X)	Longitude (Y)	Capacity (Ton)
V1	Lebak	Agricultural center	-6^{0}43'33.2" S	106^{0}15'90.5" E	256,5
V2	Labuhan	Power Plant	-6^{0}39$^{'10.9}$ "S	105^{0}53'02.9" E	153,5
V3	Pandeglang	Bioenergy plant 1	-6^{0}01'41.8" S	106^{0}05'39.7" E	140,5
V4	Bojonegara	Bioenergy Plant 2	-6^{0}29'74.5" S	106^{0}11'44.4" E	174,5
V5	Suralaya	Power plant	-5^{0}49'54.1"S	106^{0}03'35.0"E	160

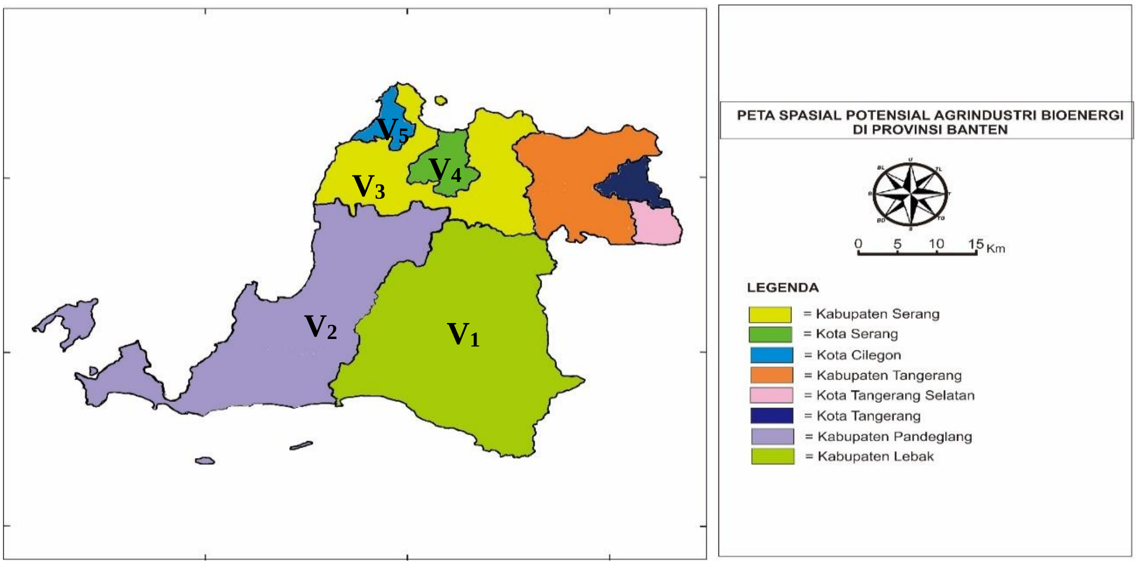


Figure 4. The map point coordinates the location

Table 2. Bioenergy distribution channels

Line	Distance (km)	Information
1-2	69,3	Lebak-Pandeglang
1-3	91,7	Lebak-labuhan
1-4	117	Lebak-Bojonegara
2-3	40,5	Pandeglang-Labuhan
2-4	50,8	Pandeglang - Bojonegara
2-5	40,5	Pandeglang-Suralaya
3-4	72,2	Labuhan - Bojonegara
3-5	80,9	Labuhan-Suralaya
4-5	19,7	Bojonegara - Suralaya

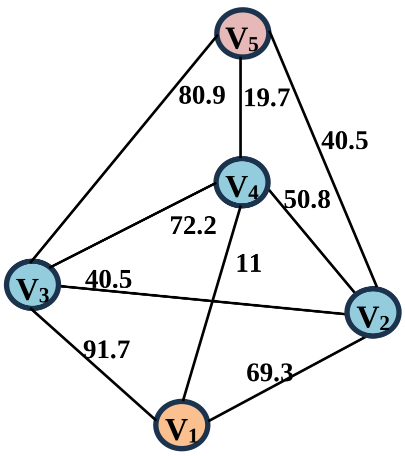


Figure 5. Network Distribution route

The criteria for road infrastructure in Indonesia vary depending on the type of road, location, and intended use. Standards are set by the Ministry of Public Works and Public Housing (PUPR).

Traffic density criteria are determined based on several primary factors: Vehicle volume, Road capacity, Average speed, traffic density, travel time, and degree of delay. Additionally, it is influenced by traffic policies and regulations established by the local government.

There are several types of natural disasters. Areas were prone to flooding, especially around the Ciujung, Cidurian, and Cilegon rivers. Some areas of the landslide zone include Cipanas, Maja, Curugbitung, and Cisimeut. The elevation is the height of a place above the surrounding area / above sea level: the size or angle of the height of a celestial body above the horizon. The average slope criterion varies depending on the type of road and local topographic conditions.

COG for Collection Center Location

Based on Equation (7), the optimal coordinates (X, Y) can be determined in Table 3. C_x^* = -5661/ 884,2 = -6,402397648; Y-coordinate determination in Table 4.

From the determination of coordinates, C_x* and C_y* are located at the center point at -60.53'42.6" S and 105.035'70.8" E, corresponding to the location of Ciandur village in Pandeglang Regency, as shown in the map of collection center locations in Figure 6.

Shortest distance with classic Dijkstra

The Dijkstra algorithm is a classical algorithm used to determine the shortest path in a graph from a source node to all other nodes. This algorithm is used to find the most concise course; it can also be adapted to determine the optimal route for distribution by considering additional factors such as transportation cost, time, or other relevant parameters. Additional factors, such as time-dependent weights or dynamic weights, need to be considered. This can be achieved by using modified versions of those algorithms or exploring alternative algorithms' determinations of the shortest distance, as shown in Figure 7.

Table 3. Optimal Coordinate

	d_{ix}	W_i	S_i	$\sum d_{ix}(W_i + S_i)$	$\sum (W_i\, n\, i = 1 + S_i)$	C_{xi}
C_{x1}	-6,73	253,50	2,55	-1723	256,5	-6,73
C_{x2}	-6,70	148,25	5,25	-1028	153,5	-6,7
C_{x3}	-6,03	135,25	5,35	-847	140,5	-6,03
C_{x4}	-6,50	167,5	6,55	-1131	174,5	-6,5
C_{x5}	-5,83	155,5	4,50	-932	160	-5,83

Table 4. Calculation of longitude (Y) coordinates $\sum (\boldsymbol{Wi\ n\ i}=\mathbf{1} + \boldsymbol{Si})$

	d_{ix}	W_i	S_i	$\sum d_{iy}(W_i + S_i)$	$\sum (W_i\, n\, i = 1 + S_i)$	C_{yi}
C_{y1}	106,27	253,5	2,55	27210,43	256,05	106,27
C_{y2}	105,89	148,25	5,25	16254,11	153,5	105,89
C_{y3}	106,09	135,25	5,35	15030,14	140,6	106,09
C_{y4}	106,19	167,5	6,55	18482,37	174,05	106,19
C_{y5}	106,05	155,5	4,5	15968	160	106,05

$$\sum d_{ix}(W_i + S_i) \,/ \sum (W_i\, n\, i = 1 + S_i)$$

$C_y{}^{*}$= 15968/ 884,2 = 105,117677

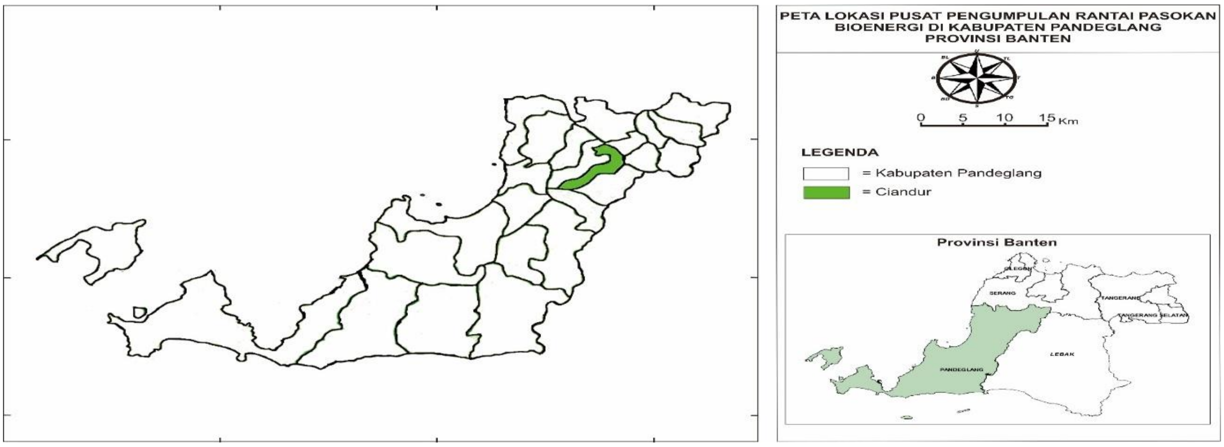


Figure 6. Collection location map

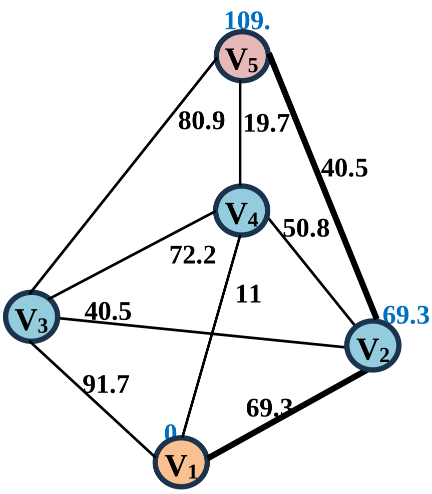


Figure 7. Shortest route with classic Dijkstra algorithm

We use a spatial perspective to determine the most optimal distribution route. We incorporate spatial aspects, namely: 1) temporal-spatial congestion. The temporal-spatial congestion comes from the observation of traffic density during the duration of 9.00-24.00; some congestion often occurs in the areas of Pandeglang (V2) to Labuhan (V3) and Bojonegoro (V4) to Suralaya (V5); 2). Road infrastructure criteria in Indonesia may vary depending on the type of road, its location, and its intended use. Standards are set by the Ministry of Public Works and Housing (PUPR); 3). Traffic density criteria are determined based on several key factors: Vehicle volume, road capacity, average speed, traffic density, travel time, and level of delay. In addition, it is also influenced by traffic policies and regulations set by the local government, 4)—hazard zone criteria. There are several types of natural disasters. Flood-prone areas are mainly around the Ciujung, Cidurian, and Cilegon rivers. Some areas included in the landslide zone include Cipanas, Maja, Curugbitung, and Cisimeut. Areas prone to landslides have steep topography and soil that is prone to landslides during heavy rains; 5) Elevation Criteria, Elevation is the height of a place above the surrounding area/above sea level: the measure or angle of the height of a celestial body above the horizon; 6). Slope Criteria, Average slope criteria vary depending on the type of road and local topographic conditions.

Selection of Optimal Distribution Route using Spatial Dijkstra

In this study, we used five nodes to define the code V = {V1, V2, ..., V5}. We measured the distance from one node point to another to determine the criterion value based on this rating scale. A five-dimensional scale was sorted from the highest to the lowest dimension to determine the scoring scale. Alternative consequences based on multi-criteria were determined based on the results of expert opinions.

Multi Ctiteria Analisis

Multi–Expert - Multi-criteria Decision-Making Method (ME-MCDM)

We propose ME-MCDM, which will be used to obtain the value of each AV. These values are then converted to numbers based on five-dimensional scales.

Then calculate the assessment of alternative 1 (A1) based on criteria (C1, C2, ..., C4) according to the preferences of five experts (E1, E2, ..., E5). The expert assessment results are presented in Table 5.

Table 5. Expert assessment table for alternative 1 (A_1)

Expert (Ei)	Path	Criteria			
		C^1	C^2	C^3	C^4
E^1	1-2	VH	VH	VH	H
E^2	1-2	VH	VH	VH	H
E^3	1-2	VH	VH	VH	H
E^4	1-2	H	H	H	M
E^5	1-2	VH	VH	VH	H

Based on the aggregation result formula

V_{11}=Min [VL v VL, M v VH, L v VH, VH v H]

V_{11}= Min [VH, VH, VH, H] = H

V_{12}, V_{13}, $V_{14,}$ and V_{15} are calculated using the same formula as V11. The aggregation result for alternative value 1 (A_1) corresponds to A_1 = H, H, H, M.

Expert aggregation value results

Q_1= Int [1 + (1 x (5 -1)/5)] = Int [1,8] = 2

The result Q_1 is converted to a criterion level of importance, where Very High (VH) = 5, High (H) = 4, Medium (M) = 3, Low (L) = 2, and Very Low (VL) = 1. So the weight value of Q_1 is Low (R). Values Q2, Q3, Q4, and Q5 were obtained in the same step as the result of the aggregation weight value in Table 6.

Table 6. Aggregation of weight values results

Weight (Q)	Score	Value
Q^1	2	L
Q^2	3	M
Q^3	3	M
Q^4	4	H
Q^5	5	VH

Value Q = {Q_1, Q_2, Q_3, Q_4, Q_5} = L, M, M, H, VH

Expert aggregations are aggregated with the result of aggregation with equations to obtain AV from A_1, where bj is the most significant order of expert judgment.

A_1= H, H, H, H, M; so that b_1= H, H, H, H, M

AV_1=Max [L^H, M^H, M^H, H^H, VH^M]

AV_1= Max [L, M, M, H, M] = H

The final result of alternative value 1 (AV_1) is H (High).

Considering the multiple conflicting criteria, the optimal distribution route chosen will be more appropriate. Four (4) inconsistent criteria are Distance, Cost, Risk, and Utilization. Calculate the criterion value using a 5-dimensional rating scale sorted from the highest / Very high (VH) to the lowest, i.e., very low (VL)—the importance scale in Table 7.

Each route has a different weight, so alternatives are arranged based on the route matrix to assess multiple options and criteria, informed by expert opinion. The importance scale and negation value are based on the Equation in Table 8.

Based on variable consistency testing from four (4) spatial variables, namely topology, road criteria, danger zone criteria, and temporal traffic density criteria. The most optimal route, based on the calculation of TAV values using Dijkstra's spatial multi-criteria, is the route with a total TAV weight of 1.700.74, where P(V1, V5) = (V1, V2, V3, V5) in Figure 8.

Table 7. The scale of importance criteria

Code	Criteria	Description	Scale of Importance
C_1	Distance	Distance to speed up delivery and distribution time.	Very High (VH) = 1
C_2	Cost	Cost savings to save time and fuel consumption.	Medium (M) = 3
C_3	Risk	Risk of a lack of resources	Height (H) = 2
C_4	Utilization	Utilities to prevent reduced raw materials	Very High (VH) = 1

Table 8. Negation Table

Code	Criteria	Scale of Importance	Negation of the scale of importance
C1	Distance	C1= VH	Negation(C1)= VL
C2	Cost	C2= M	Negation(C2)= M
C3	Risk	C3= H	Negation(C3)= L
C4	Utilization	C4= VH	Negation(C4)= VL

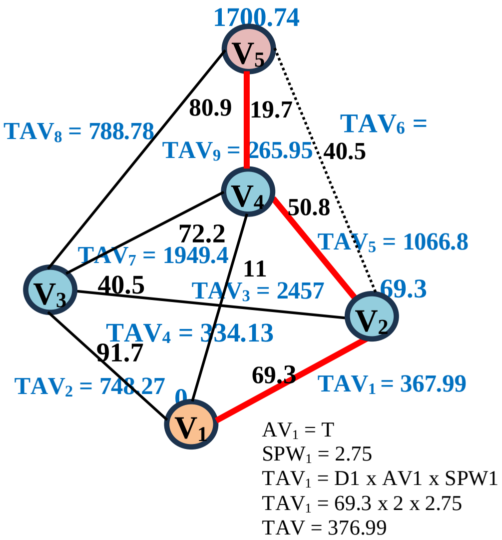


Figure 8. Single graph network with Dijkstra spatial multi-criteria

Comparison and Performance

Comparison and Performance Evaluation of Dijkstra's Spatial Multi-criteria Approach. The most optimal route (R_s) using the spatial method of Dijkstra is with the total average value, where the path (V_1, V_5) = (V_1, V_2, V_3, V_5). According to the proposed method, the spatial Dijkstra weights are TAV 1700.74, where P(V_1, V_5) = (V_1, V_2, V_3, V_5) in Table 9.

Table 9. Method comparison

Comparison	Dijkstra Classic (Existing Approach)	Multi-criteria Spatial Dijkstra (Proposal Method)
Purpose	Shortest Route	Optimal Route
Criterion	Single criteria	Multi-criteria
Basic Calculation	Distance	Multi-criteria
Focus	Transporta tion	Distribution on
Result	Distance/unit	Weight Value

The route using the classic Dijkstra algorithm is the shortest route with a distance of 109.8 via the route V_1-V_2-V_5, P (V_1, V_5) = V_1, V_2, V_5). In comparison, spatial Dijkstra is the optimal route with a weight value of 1700.74 with routes V_1-V_2-V_4-V_5, P (V_1, V_5) = (V_1, V_2, V_4, V_5)—differences in networks in Figure 9.

Development of a comprehensive method integrating economic and environmental aspects, namely the average slope of road segmentation, moderate elevation, social elements, spatial-temporal traffic density, population density, and danger zone index.

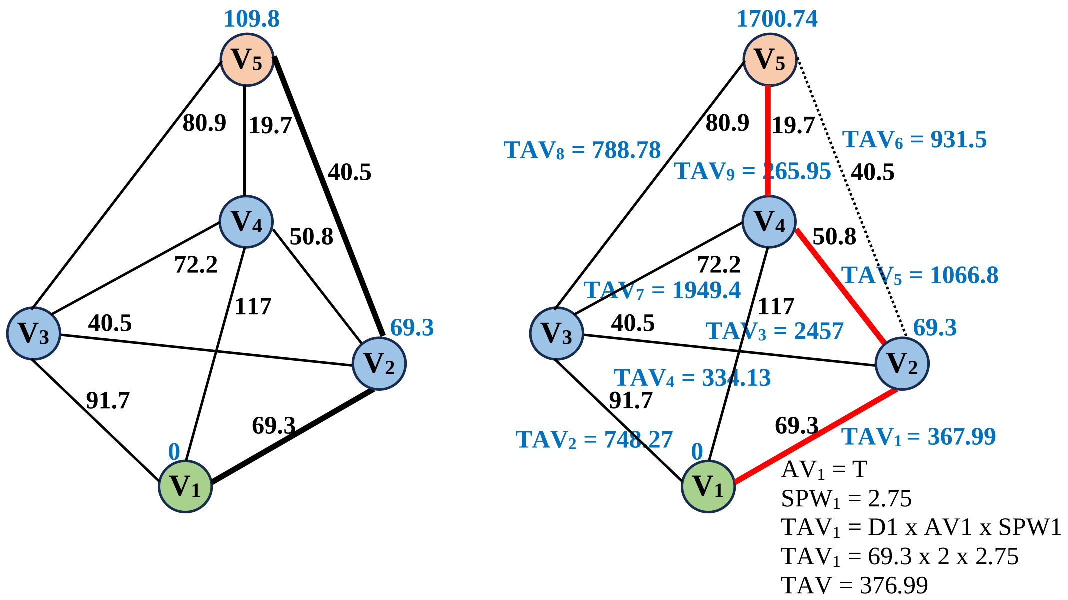
The distribution route is chosen based on a spatial perspective. The multi-criteria spatial approach, Dijkstra with AV weights from ME-MCDM, utilizes a spatial perspective with SPW. The conversion value remains AV. AV serves as the distance multiplier (d) in the spatial calculation of classical Dijkstra and SPW to obtain the TAV value.

Using spatial, the results obtained differ from those of the Classical Dijkstra. Dijkstra's spatial approach considers green criteria such as cost, distance, risk, and utility. Non-numerical ME-MCDM can address uncertainty problems with multiple criteria by incorporating expert preferences. In the initial step, applied to problem cases using the Dijkstra spatial method, routes are determined based on the shortest distance. However, in actual conditions, it is necessary to consider various criteria.

Spatial Dijkstra is used when an optimal solution is required and the environment is stable (e.g., map-based transportation route navigation). Genetic Algorithms are used if the problem is complex, large-scale, and has many changing variables for optimization problems that are dynamic and complex, such as logistics route optimization. The best choice depends on the specific needs and limitations of the system being used. Research limitations related to spatial data assumptions, resource availability, or practical implementation of algorithms have not been discussed in depth.

Managerial Implications

The model of determining the optimal distribution in the bioenergy supply chain is essential for the system's sustainability: 1) Delivery efficiency, minimizing travel distances and delivery times between various points in the bioenergy supply chain (Abdali *et al.*, 2021). 2) Supply constraints (Wang *et al.*, 2022). With optimal distribution routes, bioenergy supply can be delivered more reliably and on time to customers; precise routing takes into account factors such as distance, traffic, road conditions, and congestion to minimize the risk of delays or delivery failures. 3) Cost and emission reduction (Wang *et al.*, 2022). 4) Reducing environmental impact (Meyer and Priess, 2014).



(a) Dijkstra Classic (b) Multi-Criteria spatial Djikstra

Figure 9. Method Comparison

Determining optimal distribution routes can help reduce negative environmental impacts, including deforestation, air pollution, and land degradation. Using efficient routes can also help reduce conflicts between ecological interests.

With the determination of optimal distribution routes, the bioenergy supply chain will run more efficiently and smoothly (Techane *et al.*, 2022). This will improve overall supply chain performance, including production efficiency, waste reduction, and cost savings (Duc *et al.*, 2021); (Tesfamichael *et al.*, 2021). Performance improvement will support the growth and sustainability of the bioenergy industry as a whole (Rabbani *et al.*, 2018); (Sarkar *et al.*, 2021).

Model Verification and Validation

Validation techniques employed in this study include structural validation based on theoretical design and production behavior. Performance validity is measured by comparing model outputs' performance with actual model outputs using extreme condition tests (Sargent, 2010), unit of analysis consistency checks, and statistical data consistency checks. Dijkstra's multi-dimensional approach to determining bioenergy distribution suggests that incorporating spatial analysis can be a valuable alternative in material management, helping to balance supply and demand for a sustainable collection of bioenergy raw materials. Field trial validation has been conducted by implementing a decision support system for bioenergy distribution.

Although the application of Dijkstra's spatial model for route optimization presents significant challenges in terms of initial cost and calculation complexity, its long-term benefits to transportation efficiency, cost reduction, and environmental sustainability are substantial. With the proper implementation strategy, this model can be the optimal solution for more innovative and more efficient transportation and logistics planning.

Future Research Agenda

The view on sustainability studies is an exciting and widely discussed topic today, and it is pretty significant, particularly with the use and distribution of bioenergy as an alternative energy source. Our proposed model can serve as a sustainable alternative solution. The COG method and distribution route determination, utilizing multi-dimensional criteria essential to stakeholders, can be optimized using Dijkstra's algorithm to achieve a balance between supply and demand, making the process faster, easier, and more precise. We propose using communication and information technology.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This research contributes to determining collection locations with a more rational COG Spatial approach for bioenergy commodities. The multi-dimensional spatial Dijkstra approach provides a more reasonable solution than the classical one. Methods can verify that the best distribution route is not always the shortest route, but also need to consider complexity and uncertainty based on model verification and validation. The application of bioenergy distribution optimization using spatial-based Dijkstra's algorithm is an approach that aims to find bioenergy distribution paths. The application of bioenergy distribution optimization using Dijkstra's spatial algorithm has various managerial implications that impact planning, decision-making, operational efficiency, and the development of an efficient business strategy, considering geographical and infrastructure factors. The application of bioenergy distribution optimization using Dijkstra's spatial algorithm has a significant impact on operational efficiency, strategic decision-making, and business sustainability. Managers can conduct data-driven planning more easily, reduce operational costs, manage distribution risks more effectively, and improve customer satisfaction.

With a data-driven approach and digital technology, companies can enhance their competitiveness in the bioenergy industry and accelerate the transition to more efficient and environmentally friendly renewable energy sources.

Recommendations

The distribution of bioenergy using the multi-criteria spatial Dijkstra method is an approach that combines the shortest path search algorithm (Dijkstra) with multi-criteria spatial (geographical) considerations. The multi-criteria decision-making (MCDM) approach is necessary to consider distance as the basis for the Dijkstra algorithm, the availability of bioenergy raw materials, and the locations of production and consumption facilities (such as factories, power plants, and PLTBm). Further research can be applied to GIS software, such as ArcGIS or QGIS, with the GRASS or SAGA plugin.

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