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Spatial Planning for Transmission Line Routing using Multi-Criteria Decision Analysis

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Abstract. Through the *Electricity Supply Business Plan (RUPTL) 2021–2023*, PT PLN (Persero) outlined plans for the development of transmission systems across Indonesia, projecting an expansion of 76,662 MVA in substation capacity and 47,723 kilometres of transmission lines by 2030. Transmission infrastructure development is further detailed for each major island system in the country. In particular, the transmission network in Sulawesi remains divided into two systems: Southern Sulawesi (SULBAGSEL) and Northern Sulawesi (SULBAGUT). The RUPTL document also highlights several strategic projects in the Sulawesi transmission system, including the 150 kV Tambu–Bangkir Transmission Line. Following an instruction from the Directorate General of Electricity to accelerate the Commercial Operation Date (COD) for the Tambu–Bangkir segment to 2024, the project timeline has been adjusted accordingly and designated as a priority assignment. Current transmission line construction planning still relies on manual methods, which have several weaknesses, including route inefficiency, potential cost overruns, challenges in accessing planning locations, and low planning accuracy that often does not reflect actual field conditions. This approach also inadequately considers disaster factors and the aspects of environmental, social, and corporate governance. This research aims to develop a more effective and efficient method for transmission line planning that reduces cost overruns while improving accessibility and planning accuracy. Additionally, this study will explore ways to incorporate land use, road access, disaster factors, and environmental, social, and corporate governance considerations. Spatial modeling using the Multi-Criteria Decision Analysis (MCDA) method can offer a more comprehensive approach, making transmission line planning more optimal and sustainable.

Keywords: *Multi-criteria decision analysis; Spatial analysis; Spatial modeling; Transmission line route*

1 Introduction

Electric energy demand has become a crucial factor in daily life, closely linked to residential, industrial, and commercial growth. According to the Indonesia Energy Outlook (IEO) 2019, published by the Ministry of Energy and Mineral Resources (ESDM), electricity demand is projected to be primarily driven by the residential sector until 2050, followed by the industrial and commercial sectors. The Electricity Supply Business Plan (RUPTL) 2021-2030 of PT. PLN (Persero) anticipates a significant increase in electricity demand in the Southern Sulawesi region (Sulbagsel), particularly due to the expansion of large-scale mineral and mining processing industries. Transmission infrastructure will be enhanced throughout the Sulbagsel system to accommodate this growth. Furthermore, this transmission development aims to connect several previously isolated subsystems, including Pasang Kayu and Topoyo in West Sulawesi, as well as Ampana, Bunta, Luwuk, Tambu, Bangkir, and Toili in Central Sulawesi.[1][2] The development of transmission lines involves two key aspects: technical and economic considerations. Within the technical aspect, a crucial element is selecting tower locations along the transmission route. Currently, the planning process for determining tower sites is largely conducted using manual methods, relying mainly on visual assessments and prioritizing the shortest and safest possible route.

In this study, the author applies the Multiple Criteria Decision Analysis (MCDA) method to support the planning of transmission line routes. Previous studies have demonstrated the effectiveness of MCDA in providing location recommendations for transit-oriented development areas based on several potential indicators. To determine the relevant indicators or factors for transmission line development planning, the author conducted discussions with stakeholders at PT PLN (Persero). The influencing factors were then assigned scores and weights within each category. Spatial modeling for the MCDA method in this study was performed using ArcMap version 10.7.1.

2 Literature Review

2.1 Data Source

The first stage of this study involved discussions aimed at identifying the types of data that would serve as criteria for constructing the MCDA model. These discussions were conducted in collaboration with relevant divisions at PT PLN (Persero), including DIVRSL, the division responsible for electricity planning. Publicly available datasets were utilized, sourced from various government institutions through their official online platforms. These included the Geospatial Information Agency (Badan Informasi Geospasial/BIG), the National Digital Elevation Model (DEM), the National Disaster Management Authority (BNPB), the Ministry of Environment and Forestry (KLHK), and the Ministry of Transportation (Kemenhub). The selected data sources used in this study are listed in Table 1.[5]

Table 1 Criteria and Data Source.

Criteria	Source
Land-use Forest Area Conservation Area	The Ministry of Environment and Forestry: https://geoportal.menlhk.go.id/server/services
Topography	The Geospatial Information Agency: https://www.big.go.id/
Disaster	The National Disaster Management Authority: https://inarisk.bnpb.go.id/
Air Activity (Airport)	The Ministry of Transportation

2.2 Transmission Development Planning

In transmission line planning, it is essential to consider the existing Medium and High Voltage Transmission Network (SUTT/SUTET) systems in a specific region to ensure optimal operational performance. Generally, selecting transmission line routes involves two categories of factors: technical and non-technical considerations.[6] The following are examples of both technical and non-technical factors.

Technical Factors:

- Select the shortest possible route
- Consider efficiency by choosing areas with suitable soil bearing capacity
- Prefer relatively flat topography
- Position substations (GI) near load centers, within a maximum radius of 20 km
- Avoid areas at risk of corrosion

Non-Technical Factors:

- Choose routes that minimize social conflict by avoiding residential areas, cultural heritage sites, and nature reserves whenever possible
- Comply with spatial planning regulations; routes must align with local zoning laws
- Minimize intersections with protected areas such as conservation forests, water catchment zones, nature reserves, and national parks
- Steer clear of sensitive zones, including defense radar areas, airports, and military activity zones

2.3 GIS-MCDA (Multi-Criteria Decision Analysis)

Multi-Criteria Decision Analysis (MCDA) in Geographic Information Systems (GIS) is an approach used to address spatial decision-making problems by considering multiple, and often conflicting, criteria. This technique integrates geographic data with value-based assessments to evaluate various alternatives and derive optimal solutions. GIS-based MCDA has been widely applied in areas such as land-use planning, transmission line routing, and environmental management, with the aim of minimizing negative impacts on both the environment and surrounding communities.

The process flow diagram, as shown in Figure 1, illustrates how GIS enhances each step, from data collection and spatial analysis to MCDA modeling, to generate the optimal decision alternatives.[10]

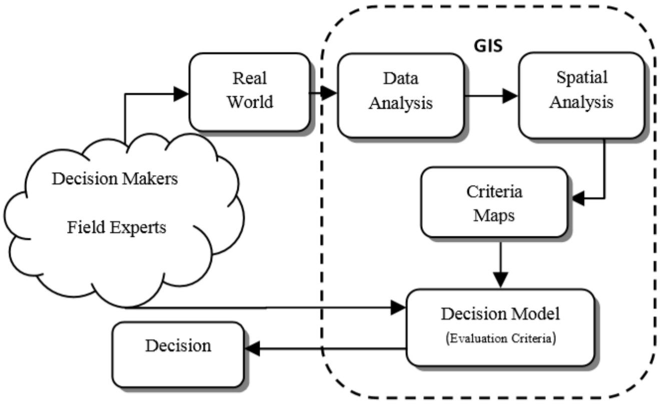

Figure 1 GIS-MCDA Approach Flowchart.

The decision-making process in this study follows a structured MCDA framework that consists of several key stages. The process begins with clearly defining the problem, objectives, and expected outcomes. A comprehensive understanding of the issue is essential to ensure that the resulting decisions are relevant and contextually appropriate. Once the objective is established, the next step involves identifying relevant criteria and constraints. This stage combines expert judgment with supporting information from historical data, existing literature, and domain-specific insights to ensure that the selected evaluation factors are valid and comprehensive.

Following criteria selection, the values associated with each criterion are transformed onto a relative scale, typically ranging from 1 to 5, to enable meaningful comparison and aggregation. This transformation allows expert knowledge to be represented in a standardized and quantifiable format. Each criterion is then assigned a weight according to its relative importance, reflecting how significantly it influences the overall decision-making objective. After weighting, the data layers are synthesized and aggregated—commonly using a weighted overlay approach—into a composite suitability map, integrating all contributing spatial variables into a unified decision-support layer.

Finally, the resulting analysis is reviewed and validated to ensure that it reflects realistic planning constraints and aligns with stakeholder expectations. This step is critical to confirm the robustness and acceptability of the proposed solution, particularly in complex spatial planning contexts such as transmission line development.

Figure 2 illustrates the principle of weighted overlay using two input raster layers, InRas1 and InRas2, which represent two different criteria. In this example, InRas1 is assigned a higher influence weight of 75%, while InRas2 carries a lower influence weight of 25%. Each cell in the input raster contains a reclassified value ranging from 1 to 3, with lower values indicating higher suitability.

The output raster (OutRas) is generated by calculating the weighted sum of corresponding cell values from both layers. For instance, a cell with a value of 2 in InRas1 and a value of 3 in InRas2 would be computed as:

$$(2 \times 0.75) + (3 \times 0.25) = 1.5 + 0.75 = 2.25$$

This process is repeated for all corresponding cells across the study area. The resulting OutRas layer thus reflects a composite suitability map, where the contribution of each criterion is proportional to its assigned weight.

By adjusting the weights based on the significance of each factor—such as giving greater influence to land use (35%) or proximity to roads (20%)—the weighted overlay ensures that the final output map aligns with planning priorities and minimizes potential risks, such as environmental conflict or accessibility issues. This approach provides a robust and transparent method for integrating multi-dimensional spatial data into a single decision-support layer for optimal transmission line routing.

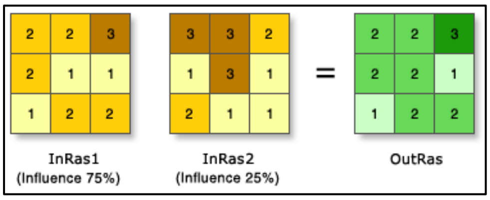

Figure 2 Weighted Overlay Ilustration

3 Methodology

This study applies a GIS-based Multi-Criteria Decision Analysis (MCDA) framework to identify an optimal transmission line corridor between Tambu and Bangkir. The methodology integrates both technical and non-technical spatial factors through a structured workflow that includes weighting, raster reclassification, spatial overlay, pathfinding, and route evaluation. The five main stages are outlined below:

3.1 Weighted Criteria

The data required to develop criteria layers were acquired from several sources, as shown in **Table 1**. Discussions regarding the factors and criteria used in this study were conducted in collaboration with the Business Process Owner (BPO) and power system planning experts at PT PLN (Persero). These discussions resulted in a more detailed set of criteria and sub-criteria it is used as a justification for determining the weighting. The weight for each criterion and sub-criterion was also established during this process. The highest weight was assigned to the land-use criterion, accounting for 35%, due to its frequent direct interaction with external stakeholders, particularly in land acquisition for transmission tower sites. Land acquisition involving residential areas, plantations, rice fields, and fishponds often faces challenges in reaching mutual agreements. The second-highest weight, 20%, was assigned to the sub-criterion of proximity to main roads. This factor is considered critical due to its influence on accessibility and ease of maintenance for transmission towers and lines. **Table 2** presents the discussion results, outlining the factors, criteria, sub-criteria, and corresponding weights.

Table 2 Criteria details and weighting.

Factors	Criteria	Sub-Criteria	Weight
Environment	Forest Area	Protected Forest	
		Permanent production forest	10%
		Limited production forest	
	Conservation Area	National Park	
		Nature Reserve	10%
		Wildlife Sanctuary	
Social	Land-use	Plantations	
		Settlements	35%
		Rice Fields	
		Fishponds	
Geotechnical	Topography	Slope	10%
		Main Roads Proximity	20%
Security	Disaster	Landslide Hazard	5%
		Earthquake Hazard	5%
Air Activity	Air Activity	Airport Proximity	5%

3.2 Raster Reclassification

After generating the raster layers, each criterion was reclassified using a standardized scale ranging from 1 to 5, where lower values indicate higher priority or suitability for transmission line routing. This classification approach reflects the principle that areas with lower scores are more desirable for route placement, based on factors such as minimal environmental impact, easier land acquisition, or technical feasibility. **Table 3** shows examples of the reclassification results for each criterion.

Table 3 Ciriteria Reclassification for slope, main roads and airport proximity, landslide and earthquake hazard index.

Slope	Main Roads Proximity	Airport Proximity	Landslide hazard Index	Earthquake hazard Index	Reclassified Value
0 to 5 °	<500 m	>15 km	0 to 0.2	0 to 0.2	1
5 to 15 °	500 to 1000 m	10 to 15 km	0.2 to 0.4	0.2 to 0.4	2
15 to 30 °	1000 to 1500 m	6 to 10 km	0.4 to 0.6	0.4 to 0.6	3
30 to 45 °	1500 to 2000 m	4 to 6 km	0.6 to 0.8	0.6 to 0.8	4
>45 °	>2000 m	<4 km	0.8 to 1	0.8 to 1	5

Reclassification plays a critical role in the overall outcome of a weighted overlay analysis, as it standardizes diverse input data into a common scale that allows for meaningful comparison and integration. In the context of this study, reclassification transforms raw input values—such as slope angle, land use types, distance to infrastructure, and hazard indices—into a unified ordinal scale (1 to 5), where lower values represent higher suitability for transmission line routing. The accuracy and rationale behind the reclassification process directly influence the integrity of the final suitability map. For instance, an underestimated hazard index or an overly generalized land use class may bias the outcome, leading to the inappropriate prioritization of certain areas. Each class is aligned with the criterion's real-world implications by carefully defining value ranges during reclassification. This ensures that when layers are weighted and combined, the aggregated score truly reflects the spatial priorities of the planning objective. In the earthquake hazard index example, areas with lower seismic risk (index 0–0.2) were assigned the lowest reclassified value (1), thus contributing more positively to the suitability score. Conversely, areas with higher seismic risk (index >0.8) received the highest value (5), reducing their desirability in the final map. When this reclassified layer is overlaid with other layers, such as land use or proximity to roads, the cumulative impact is shaped not only by the weight of the layer but also by how its values were classified. Effective reclassification ensures that the weighted overlay produces a balanced and realistic representation of spatial suitability, preventing skewed results and enabling more informed decision-making in infrastructure development planning. Figure 3 shows the differences in raster values before and after the reclassification process.

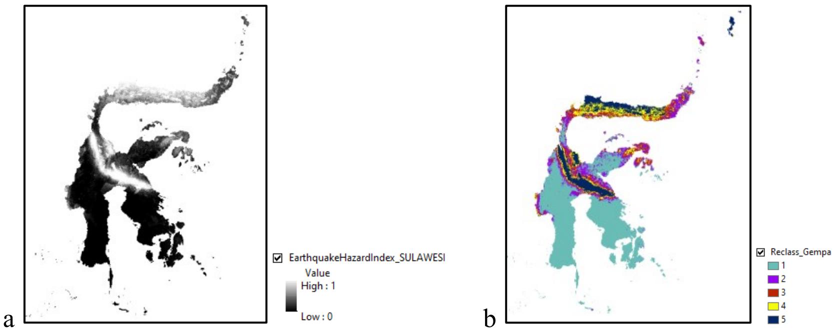

Figure 3 (a) Earthquake Hazard Index before reclassification; (b) Earthquake Hazard Index after reclassification

3.3 Overlaying of all the reclassified criteria

In the MCDA framework applied in this study, each spatial criterion contributes differently to the overall suitability analysis. To account for this, a weighted overlay method was employed, in which each reclassified raster layer was assigned a specific weight based on its relative importance, as determined through expert consultation with power system planners and the Business Process Owner (BPO) at PT PLN (Persero).

All reclassified raster criteria were weighted and combined into a single output layer, where each pixel has a suitability value ranging from 1 to 5, forming the base layer for the Multi-Criteria Decision Analysis (MCDA), as shown in **Figure 4**. The Weighted Overlay tool in ArcMap was used to perform this integration, applying weights to each criterion based on the prior agreement outlined in **Table 2**. These weights reflect the relative influence of each factor on transmission line planning. The weighted overlay process produced a composite raster layer that highlights spatial suitability, with lower scores indicating higher priority areas for potential transmission routes.

The MCDA layer resolutions used in this study were 100 × 100 meters and 350 × 350 meters, serving as the basis for comparison in the pathfinder analysis that generated the proposed transmission route from Tambu to Bangkir. The finer resolution (100 × 100) aimed to provide more detailed spatial insights, while the coarser resolution (350 × 350) aligned with the average distance between transmission towers, enabling a more practical representation of route alignment.

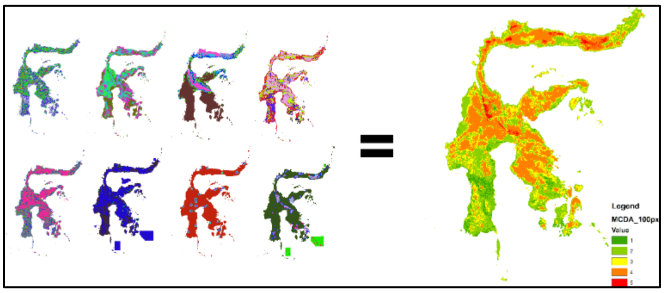

Figure 4 Weighted overlay result combining all reclassified raster criteria into a single MCDA suitability map

3.4 Pathfinder Analysis

The pathfinder analysis in this study employed ArcMap's Spatial Analyst tools to identify the optimal transmission route from Tambu to Bangkir based on the MCDA cost surface. The process began with the Cost Distance tool, which calculated the accumulated travel cost from the source point (Tambu substation) across the study area, generating a cost distance surface based on the weighted MCDA raster. This was followed by the Cost Path tool, which traced the least-cost route from the destination point (Bangkir substation) back to the source through the cost surface, identifying the path of lowest cumulative cost. Finally, the Raster to Polyline tool converted the raster-based path into a vector format, allowing for clearer visualization and further analysis. The entire workflow was implemented using Model Builder in ArcMap to streamline the analysis, including the Cost Distance, Cost Path, and Raster to Polyline tools. This model-based approach allowed for the automation of the least-cost path generation, enabling all tools to be executed in a single run. As a result shown in the **Figure 5**, the analysis efficiently produced a vector layer representing the proposed transmission line route from Tambu to Bangkir, significantly reducing processing time and minimizing potential human error in manual execution. Figure 6 displays the blue line representing the planned transmission route from Tambu to Bangkir, generated through the pathfinder analysis. It is clear that the line consistently follows areas with lower cost values, primarily those displayed in green. This line serves as a preliminary survey reference for transmission route planning and does not necessarily indicate the final alignment of the transmission infrastructure.

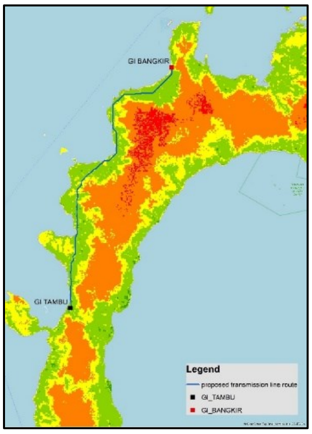

Figure 5 Result of the pathfinder analysis showing the proposed transmission line route from Tambu to Bangkir

3.5 Calculating total value on proposed line route

The total value of all raster cells traversed by each route was calculated to assess the optimality of the routes generated by the pathfinder analysis. The ArcMap "Extract by Mask" tool was utilized for this purpose, generating raster data by extracting cells from the raster layer MCDA corresponding to areas defined by the route as a mask. The resulting output provides quantitative information regarding route suitability, enabling direct comparison of total accumulated cost values for each evaluated transmission route. **Figure 6** presents the result of the Extract by Mask process applied to the MCDA layer with 100 × 100 m resolution, using the polyline of the proposed transmission route as the mask. The extracted output comprises 1,252 raster cells, each with associated suitability values. The composition includes 137 cells with a value of 1, 1,088 cells with a value of 2, and 27 cells with a value of 3. By multiplying the number of cells by their respective values and summing the results, the total cumulative cost for this route is calculated as 2,394 units. This calculation method was also applied to the other two proposed transmission routes: (1) the path generated from the MCDA layer with 350 × 350 m resolution, and (2) the transmission line alignment from the RUPTL 2021–2030, overlaid on the 100 × 100 m MCDA layer.[9]

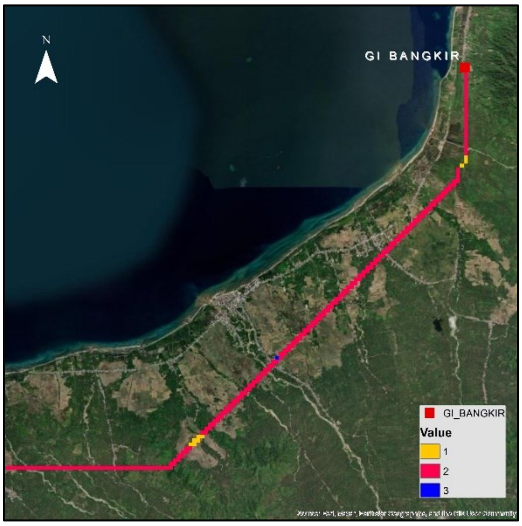

Figure 6 Extracted raster cells along the proposed transmission line route

4 Result and discussion

First, the line generated through the pathfinder analysis is a preliminary reference for the transmission route planning survey. As discussed earlier, a comparative assessment was conducted by calculating the total value of the raster cells traversed by each line on the MCDA layer. Three routes were evaluated in this analysis: (1) the path generated from the MCDA layer with a resolution of 100 × 100 m, (2) the path derived from the MCDA layer with a resolution of 350 × 350 m, and (3) the reference route drawn based on the RUPTL 2021–2030, which is overlaid on the MCDA layer with a resolution of 100 × 100 m.

In the initial phase of the analysis, the selected resolution of 350 × 350 meters for the MCDA layer aligns with the average spacing between transmission towers, which is approximately 350 meters. This resolution was deemed adequate for modelling the spatial extent of Sulawesi Island, resulting in a raster composed of 2,539 columns and 3,105 rows. However, during the evaluation process, it became evident that the transmission route generated using this layer could potentially be further optimized. This realization led to developing a second MCDA layer with a finer resolution of 100 × 100 meters, allowing for a more detailed spatial analysis and comparison. Following the same processing workflow in ArcGIS—from data preprocessing to the weighted overlay—the higher-resolution MCDA layer was successfully generated. This version contains 8,907 columns and 10,865 rows, significantly enhancing the spatial detail across the same geographic area. The resulting comparison underscores that the finer resolution enables the pathfinder analysis to better capture local terrain variations and land characteristics, which can affect routing decisions. Consequently, the increased granularity of the 100-meter resolution contributes to a more precise comparison identification of suitable transmission corridors, which is critical for minimizing costs and reducing environmental or social conflicts in future development stages.

In addition to pixel distribution, the total cumulative cost was calculated for each transmission line route by summing the product of the number of pixels and their respective reclassified values, as described in the methodology section (Calculating Total Value on Proposed Line Route). The comparison of cumulative costs is presented in **Table 4** and **Figure 7**. The proposed route generated using the 100 × 100 m MCDA layer yielded the lowest cumulative cost of 2,394, confirming its alignment with the most suitable land classifications. This was followed by the 350 × 350 m resolution route, which resulted in a slightly higher cost of 2,845, indicating that, while still optimal, the coarser resolution limited the model's ability to accurately navigate low-cost areas.

In stark contrast, the RUPTL route incurred the highest cumulative cost of 4,292, almost 80% higher than the 100 m route. This significant discrepancy reinforces earlier observations that the RUPTL alignment intersects large areas with pixel values 4 and 5 zones classified as less suitable for transmission development. As previously discussed, this can be attributed to the RUPTL route's derivation through visual interpretation without spatial constraint analysis, which results in a quasi-linear path that disregards terrain, land use, or environmental sensitivity.

This quantitative evidence highlights the clear advantage of using data-driven, GIS-based MCDA approaches for transmission planning. Higher-resolution spatial modelling not only provides more granular control in selecting favourable terrain but also translates into substantial reductions in potential development cost and environmental impact.

Table 4 Comparison of proposed transmission line route

Proposed transmission line route	Pixel count per value					Total cumulative cost
	1	2	3	4	5	
100x100m	137	1088	27	0	0	2394
350x350m	99	1241	88	0	0	2845
RUPTL	2	241	142	518	262	4292

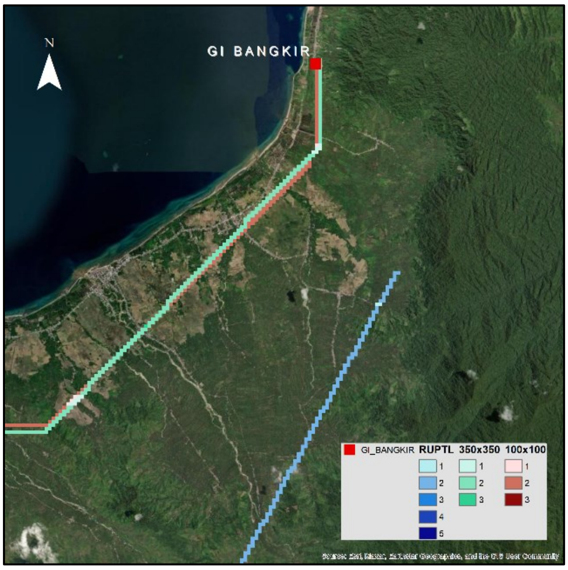

Figure 7 Comparison of proposed transmission line route

5 Conclusion

The results of this study demonstrate that a GIS-based Multi-Criteria Decision Analysis (MCDA) approach, when supported by high-resolution spatial data and systematic weighting of relevant factors, offers significant advantages in transmission line planning. Among the three routes analyzed, the pathfinder-generated route using the 100 × 100 m MCDA layer proved to be the most optimal in terms of spatial suitability and cost-efficiency, achieving the lowest cumulative cost (2,394) and avoiding high-cost areas entirely. In comparison, the route generated using the 350 × 350 m resolution also performed relatively well but showed a moderate increase in cumulative cost (2,845), likely due to reduced spatial granularity which limits its ability to finely navigate around constraints. Meanwhile, the RUPTL-based route, derived without spatial analysis and largely based on visual approximation, intersected substantial portions of land with low suitability and resulted in the highest cumulative cost (4,292). This indicates a high potential for environmental, technical, and socio-economic challenges in its implementation.

Overall, the comparison clearly highlights the critical role of spatial resolution and data-driven analysis in optimizing infrastructure planning. The findings support the adoption of MCDA-GIS methodologies, particularly with finer resolution inputs, for more sustainable, cost-effective, and technically sound transmission line development.

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