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A Spatial-Based Planning Analysis for Transmission Line Development Using the Multi-Criteria Decision Analysis (MCDA) Approach

Juzd Thoha Chairul Anam[1], Rinovia Mery Garnierita Simanjuntak[2], Anggi Afif Muzaki[3]
[1,2]Institut Teknologi Bandung, Indonesia; [3]PT. PLN (Persero), Indonesia
Email: 20923016@mahasiswa.itb.ac.id, rino@itb.ac.id, anggi.muzaki@pln.co.id

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 kilometers 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

Corresponding: Juzd Thoha Chairul Anam
E-mail: 20923016@mahasiswa.itb.ac.id

INTRODUCTION

Electric energy demand has become a key driver of development, especially in Indonesia, where rapid urbanization and industrial expansion significantly influence electricity consumption (Gielen, 2018; Leydon & Tharakan, 2020). According to the Indonesia Energy Outlook 2019 published by the Ministry of Energy and Mineral Resources, the residential sector will remain the largest contributor to electricity demand until 2050, followed by industrial and commercial sectors (ESDM, 2019). This projection aligns with studies emphasizing the rising consumption in developing economies due to lifestyle changes and increasing electrification rates (Amri et al., 2021). The Electricity Supply Business Plan (RUPTL) 2021–2030 from PT. PLN (Persero) further highlights the anticipated surge in electricity demand in the Southern Sulawesi region (Sulbagsel), largely due to the expansion of large-scale mineral and mining industries (PLN, 2021). Addressing this, significant transmission infrastructure is planned to link isolated subsystems, aiming for a more resilient and integrated grid (IEA, 2021). Despite such plans, the current method for determining transmission tower sites remains largely manual, based on visual assessments, which may lead to suboptimal planning (Musa et al., 2020). The application of GIS-based multi-criteria decision analysis has been recommended globally to enhance efficiency and reduce human error in transmission routing (Kalogirou & Bojic, 2021). In addition, integration with smart grid technology and renewable sources is crucial to ensuring long-term system flexibility and economic sustainability (Ramli et al., 2022).

Despite projections of rising demand, transmission planning in Indonesia remains largely manual—primarily based on visual route inspections—leading to inefficiencies including cost overruns and stakeholder conflicts during land acquisition (Musa et al., 2020; Tumiran et al., 2021). A 2022 report from Indonesia's Directorate General of Electricity noted that approximately 40 % of delayed transmission projects in Sulawesi were due to poor route planning and community disputes, underscoring weak integration of environmental and social governance (ESG) considerations (OECD, 2024). This manual approach exacerbates project delays and inflates costs, as noted in Sulawesi's interconnection plans where isolated subsystems require coordinated routing (Tumiran et al., 2021; JICA, 2008). Moreover, World Bank analysis highlights that technical and E&S deficiencies in planning often lead to increased grid losses and schedule slippages (World Bank, 2023). International best practices recommend GIS-based multi-criteria decision analysis to simulate optimal tower siting, minimizing both environmental impact and stakeholder resistance (Kalogirou & Bojic, 2021; Ruiz et al., 2020). Integrating these data-driven methodologies is imperative to improve planning accuracy, promote sustainable development, and ensure ESG compliance in future transmission projects (OECD, 2024).

In this study, the author applies the Multiple Criteria Decision Analysis (*MCDA*) method to support the planning of transmission line routes (Schito et al., 2018). 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.

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.

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. 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 1 Criteria details and weighting.

Factors	Criteria	Sub-Criteria	Weight
Environment	Forest Area	Protected Forest	10%
		Permanent production forest	
		Limited production forest	
	Conservation Area	National Park	10%
		Nature Reserve	
		Wildlife Sanctuary	
Social	Land-use	Plantations	35%
		Settlements	
		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%

Source: Results of a consultation with BPO PT PLN and electricity system planning experts

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 4 shows examples of the reclassification results for each criterion.

Table 2 Criteria 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

Source: Author's reclassification standards based on BIG guidelines for slopes and BNPB's INARISK data for hazard index

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.

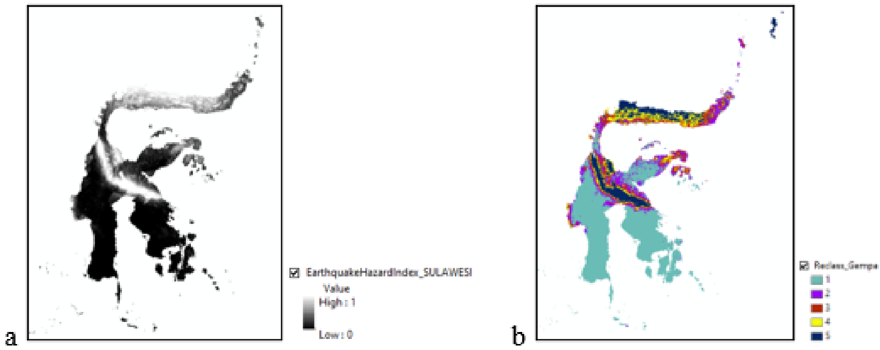

Figure 1(a) Earthquake Hazard Index before reclassification; (b) Earthquake Hazard Index after reclassification
Source: Data processed

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 5. 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.

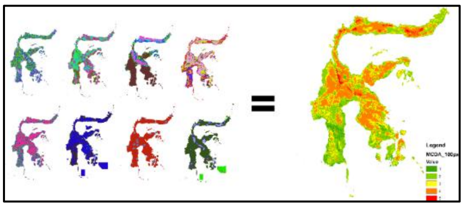

Figure 2Weighted overlay result combining all reclassified raster criteria into a single MCDA suitability map
Source: The author's analysis results using ArcGIS 10.7.1

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, 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.

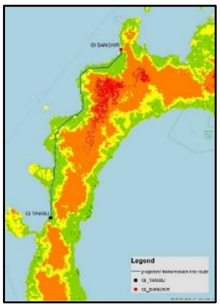

Figure 3Result of the pathfinder analysis showing the proposed transmission line route from Tambu to Bangkir
Source: Author modeling with ArcGIS Spatial Analyst tools

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. Fig. 7 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 4Extracted raster cells along the proposed transmission line route
Source: Author's analysis with the "Extract by Mask" tool on ArcMap, using MCDA 100×100m data, 2023

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. 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 favorable terrain but also translates into substantial reductions in potential development cost and environmental impact.

Tabel 3. 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

Source: Cumulative calculation of the author's fees based on MCDA analysis of 100×100m, 350×350m, and RUPTL routes

Figure 5. Comparison of proposed transmission line route
Source: Overlay of RUPTL 2021-2030 data with the results of the author's MCDA analysis

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.

REFERENCES

Amri, F., Apergis, N., & Rault, C. (2021). Electricity consumption and economic growth nexus: Evidence from advanced and emerging economies. *Energy Reports, 7*, 156–162. https://doi.org/10.1016/j.egyr.2021.02.011

ESDM (Ministry of Energy and Mineral Resources). (2019). *Indonesia Energy Outlook 2019*. https://www.esdm.go.id/assets/media/content/content-indonesia-energy-outlook-2019-english-version.pdf

Gielen, D. (2018). Forecasting Indonesia's electricity load through 2030 and peak. *Energy Procedia, 153*, 109–116. https://doi.org/10.1016/j.egypro.2018.10.019

IEA. (2021). *An energy sector roadmap to net zero emissions in Indonesia*. International Energy Agency. https://www.iea.org/reports/an-energy-sector-roadmap-to-net-zero-emissions-in-indonesia

JICA. (2008). Chapter 6 Transmission Development Planning. In *Transmission Development Planning for Sulawesi System* (pp. 6-1–6-3). Japan International Cooperation Agency.

Kalogirou, S. A., & Bojic, M. (2021). Application of GIS and multicriteria decision analysis in selecting suitable locations for electricity transmission lines. *Renewable and Sustainable Energy Reviews, 137*, 110610. https://doi.org/10.1016/j.rser.2020.110610

Leydon, R., & Tharakan, P. (2020). Electricity demand and socioeconomic development in ASEAN: A panel data approach. *Energy Economics, 92*, 104951. https://doi.org/10.1016/j.eneco.2020.104951

Musa, S. M., Hashim, M., & Jahi, J. M. (2020). Optimization of power transmission line routing using GIS and remote sensing techniques. *Geocarto International, 35*(1), 67–79. https://doi.org/10.1080/10106049.2018.1501597

OECD. (2024). *Responsible business conduct for sustainable infrastructure in Indonesia*. OECD Business and Finance Policy Papers.

PLN (Persero). (2021). *Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) 2021–2030*. PT PLN. https://web.pln.co.id/statics/uploads/2021/10/ruptl-2021-2030.pdf

Ramli, M. A. M., Bouchekara, H. R. E. H., & Alghamdi, A. S. (2022). Smart grid development in Indonesia: Challenges and future directions. *Renewable Energy, 186*, 1234–1244. https://doi.org/10.1016/j.renene.2022.01.034

Ruiz, H. S., Sunarso, A., Ibrahim-bathis, K., Murti, S. A., & Budiarto, I. (2020). GIS AHP multi decision criteria analysis for the optimal location of solar energy plants in Indonesia. *arXiv*. https://doi.org/10.48550/arXiv.2007.15351

Schito, J., Wissen Hayek, U., & Raubal, M. (2018). Enhancing mulit criteria decision analysis for planning power transmission lines. *10th International Conference on Geographic Information Science (GIScience 2018)*, *114*, 15.

Tumiran, Putranto, L. M., Irnawan, R., Sarjiya, Priyanto, A., Isnandar, S., & Savitri, I. (2021). Transmission expansion planning for the optimization of renewable energy integration in the Sulawesi electricity system. *Sustainability, 13*(18), 10477. https://doi.org/10.3390/su131810477

World Bank. (2023). *Indonesia Power Transmission Development Project (P117323)*. The World Bank.