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IMPLEMENTATION OF TRIPLE BOTTOM LINE PRINCIPLES IN INFRASTRUCTURE PROJECTS IN NORTH SULAWESI

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ABSTRACT

This study investigates integrating Triple Bottom Line (TBL) principles—social, economic, and environmental—into infrastructure planning and evaluation in North Sulawesi through a sequential mixed-methods design. First, a Cost–Benefit Analysis (CBA) estimated Net Present Value (IDR 45.2–85.4 billion), Benefit–Cost Ratio (1.1–1.8), and Internal Rate of Return (9.5 % over 30 years), confirming economic viability. Simultaneously, a Life Cycle Assessment (LCA) quantified material-related energy use and CO_2e emissions, while structured surveys and focus-group discussions captured community perceptions of benefit distribution and participation. These quantitative and qualitative insights were synthesized in a Multi-Criteria Decision Analysis (MCDA) employing the Analytic Hierarchy Process (AHP), where twelve experts assigned weights of 0.441 (social), 0.301 (environmental), and 0.258 (economic). Among three strategic alternatives, a low-emission public-private partnership scored highest (0.83) by combining robust stakeholder engagement, recycled-steel use with offset mechanisms, and strong long-term returns; sensitivity analysis (±10 % environmental weight) confirmed its ranking stability. By mapping outcomes to SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), the study demonstrates that a TBL-based framework can simultaneously secure financial performance, advance social equity, and reduce environmental impact. Recommendations include formalizing hybrid financing, enhancing participatory platforms, and incentivizing low-carbon materials.

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INTRODUCTIONS

Infrastructure development has long been recognized as the backbone for economic growth, equitable access to basic services, and improved quality of life (Joshua, 2019). Adequate infrastructure, be it road networks, clean water supply, energy availability, or waste management systems, creates the foundation for productive activities and strengthens social resilience (Mehraban et al., 2025). At the global level, the Sustainable Development Goals (SDGs) framework underscores the importance of sustainable production and consumption (SDG 12)(Hales & Birdthistle, 2023), improved infrastructure (SDG 9) (Mahmoud et al., 2025), sustainable cities and communities (SDG 11) (Küfeoğlu, 2022; Nabiyeva et al., 2023), and action on climate change (SDG 13) (Arora & Mishra, 2023). However, when these goals are translated into local contexts, especially in outer regions and islands such as North Sulawesi, the implementation challenges become complex and layered (Pfe, 2019; Sever & Tok, 2025).

North Sulawesi is a province at the northern tip of Sulawesi Island that geographically consists of coastal plains, high mountains, and small islands (Law & Jeffrey, 2014). The combination of monsoon winds, heavy rainfall, and rugged topography creates technical challenges in building a reliable road network throughout the year (Shrestha, 2025). At the same time, regional economic growth based on agriculture, fisheries, and tourism requires reliable road access to distribute crops, handle marine production, and facilitate ecotourism (Rawung et al., 2023). Although the government has allocated large budgets since the era of regional autonomy, realization on the ground is often constrained by natural conditions, gaps in implementing capacity, and inter-regional coordination issues (Guerrero & Castañeda, 2022; Khairin et al., 2022).

While most district towns have treatment and distribution systems in the clean water sector, rural areas and small islands still rely heavily on shallow wells and small-scale water towers (Grigg, 2024; Z. Wang et al., 2025). According to WHO standards, at least one in four villages does not have adequate access to safe drinking water and sanitation (Singh & Jayaram, 2022). This poses health risks, high rates of waterborne diseases, and an economic burden to purchase bottled water (Islam, 2025; Shayo et al., 2023). The water scarcity crisis is not only about volume availability, but also the quality of pipeline maintenance, distribution system leakage, and domestic waste management capacity (Scarcity, 2020).

Similarly, North Sulawesi is still heavily dependent on electricity supply from the Java-Madura-Bali grid in the energy sector through inter-island transmission lines (Lumi & Budiarto, 2022). In several remote zones, rolling blackouts and voltage fluctuations are part of people's daily lives (Raza et al., 2022). The potential for renewable energy, including micro-hydro in mountain creeks, solar power in highlands with minimal cloud cover, and wind potential on the west and north coasts, is enormous(Balkishan et al., 2018). However, the main obstacles are financial constraints, a lack of comprehensive feasibility studies, and limited technology development capacity (Elshaarawy & Ezzat, 2023; Minetti et al., 2019).

The waste management system also shows significant gaps in environmental governance (Awino & Apitz, 2025). The practice of open dumping in several coastal areas and unmanaged liquid waste disposal triggered river pollution and inadequate landfills (Al-Wabel et al., 2022; Nwokike, 2021; Siddiqua et al., 2022). As a result, coastal ecosystems and coral reefs began to show damage, while greenhouse gas emissions from organic decomposition and waste combustion increased without control (Perricone et al., 2023; Reed et al., 2022). Public awareness and technological infrastructure for 3R-based waste management (reduce, reuse, recycle) still need to be improved through incentive policies, environmental awareness campaigns, and cross-sectoral institutional strengthening (Vita et al., 2023; Yasmeen et al., 2023).

These challenges emphasize that conventional infrastructure development approaches, which generally only address the economic viability of projects, will not be sufficient to achieve the 2030 SDGs (Han et al., 2021; Khan, 2024). Measuring success only from the financial dimension or technical utility of projects ignores the long-term social impacts and environmental damage that can erode natural capital and create high externality costs (Ekins & Zenghelis, 2021). This is where the Triple Bottom Line (TBL) framework becomes relevant, as it requires decision-makers to not only pursue profit, but also consider the welfare of the community (people) and maintain environmental sustainability (planet) (Chirit, 2025; Tseng et al., 2020; Zaharia & Zaharia, 2021).

The TBL framework offers a set of principles that integrate all three pillars into the project planning, implementation, and evaluation process (Purvis et al., 2019). In the economic pillar, the Cost-Benefit Analysis (CBA) method is used to quantitatively calculate the net benefits of the project compared to the costs incurred from initial capital, operating costs, and long-term maintenance (Jiang & Marggraf, 2021; Kadigi et al., 2021). On the social pillar, data collection on community perceptions through structured surveys and Focus Group Discussions (FGDs) explored acceptability, inclusiveness, and benefit distribution (Palinkas et al., 2025). The environmental pillar uses Life Cycle Assessment (LCA) to assess environmental impacts throughout the project life cycle, from raw material extraction to final disposal, and emissions monitoring to verify field data(Moutik et al., 2023). After each dimension was analyzed, an Analytic Hierarchy Process (AHP)-based Multi-Criteria Decision Analysis (MCDA) framework combined the results into a balanced weighting model and ranked policy alternatives (Colapinto et al., 2020; Szabo et al., 2021).

While the application of TBL in significant cities and developed countries has been widely reported, empirical studies in the context of border provinces and islands such as North Sulawesi are still minimal. Most studies focus on one aspect, such as CBA studies on toll road projects or LCA on green buildings, without integrating across dimensions(Madadizadeh et al., 2024; Rattanakunuprakarn et al., 2024; Trovato et al., 2020). North Sulawesi needs a framework that can bridge the gap between national development targets and locally specific conditions: dispersed geography, sensitive ecology, and heterogeneous communities. Without integrating social and environmental dimensions, investment decisions can result in a benefits gap, where particular groups benefit too much. In contrast, other groups or ecosystem systems bear the brunt of externalities.

Based on this reality, this research was designed with four primary focuses. First, an evaluation of the economic viability of infrastructure in North Sulawesi through CBA to provide a measurable profile of costs and benefits. Second, a field study utilizing surveys and FGDs will assess community perceptions of fairness in benefit distribution and potential social conflicts. Third, environmental impact analysis uses LCA and emissions monitoring to determine the project's ecological footprint throughout its life cycle. Fourth, the development of an MCDA-AHP model that integrates the results of the three dimensions into a decision support framework, so policymakers can prioritize optimal and sustainable interventions.

Overall, this article is expected to make two main contributions. The practical contribution is a sustainable infrastructure management model that can be adopted by provincial and district governments in North Sulawesi, as well as donor agencies or development partners for evidence-based decision-making. The academic contribution is enriching the literature on TBL applications in peripheral and island contexts, which are still under-researched. By systematically integrating economic, social, and environmental elements, it is expected that infrastructure development in North Sulawesi will not only achieve technical and financial performance targets but also generate equitable social benefits and maintain environmental integrity for future generations.

RESEARCH METHODS

This research used a mixed-methods approach with a sequential explanatory design. The quantitative phase was conducted first for economic and social analysis, followed by the qualitative phase (FGDs and in-depth interviews) to enrich the findings. The final integration phase used MCDA-AHP.

A sequential explanatory mixed methods method was chosen to combine the strengths of quantitative analysis and qualitative insights (Bowen et al., 2017). The quantitative approach provides an objective picture of the economic, social, and environmental impacts through NPV, BCR, IRR, and CO_2e footprint indicators(Alomoto et al., 2022; Okay et al., 2024a; Recha et al., 2024). Furthermore, the qualitative phase through FGDs and in-depth interviews allowed exploration of local perceptions and contexts, so policy recommendations could be developed based on solid empirical evidence relevant to the dynamics of North Sulawesi society.

The study was conducted in five districts in North Sulawesi: Minahasa, North Minahasa, South Minahasa, Bitung, and Manado. The quantitative population was project-affected household heads, with a survey sample of n=400. The qualitative population included community leaders, the PUPR Office, and local academics (n=25 informants). The distribution of samples and informants in the five districts/cities can be seen in Table 1 below.

Table 1. Sample Distribution for 5 Districts/Cities

District/City	Population	Proportion (%)	Number of Respondents	Number of Informants
Minahasa	355 120	23,17	46	6
North Minahasa	235 630	15,37	31	4
South Minahasa	242 490	15,82	32	4
Manado	462 080	30,15	60	8
Beetle	237 430	15,49	31	3

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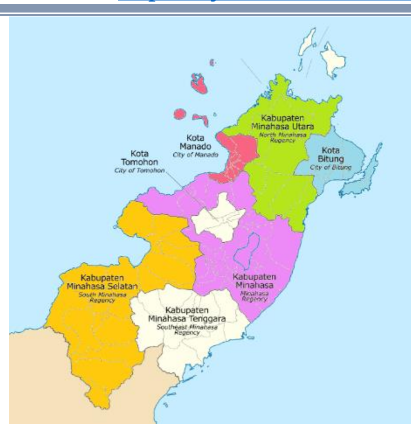

Fig. 1. Research Location

Figure 1 shows the research locations in five colored regencies/cities

Data Collection Technique

This study's data collection was conducted comprehensively using a combination of secondary data, quantitative data, and qualitative data, aiming to provide a holistic picture of the application of *Triple Bottom Line* (TBL) principles in infrastructure projects in North Sulawesi. This multi-source and multi-method approach was designed to ensure data triangulation to enhance the validity and reliability of the findings.

RESULTS AND DATA ANALYSIS

Quantitative Survey Results

The following presents summary descriptive statistics of the three key metrics measured in the survey of 400 respondents. This data is important for understanding community perceptions of the project.

Table 2. Survey Descriptive Statistics

Metrics	Mean	SD
BCR	1.39	0.35
NPV (billion)	47.45	20.10
Perception Index	3.03	1.21

Table 1 shows that the average BCR value was 1.39 (SD = 0.35), indicating that most respondents considered the project to provide positive economic benefits. The average NPV of 47.45 billion (SD = 20.10), ranging from -10.9 to 103.9 billion, explains the variation in financial risk perception. The average Perception Index of 3.03 (SD = 1.21) indicates the tendency of respondents to view the project positively or neutrally. Figure 1 complements Table 1 by displaying the distribution pattern of the Perception Index.

JURNAL ILMIAH ILMU PENDIDIKAN DAN SOSIAL
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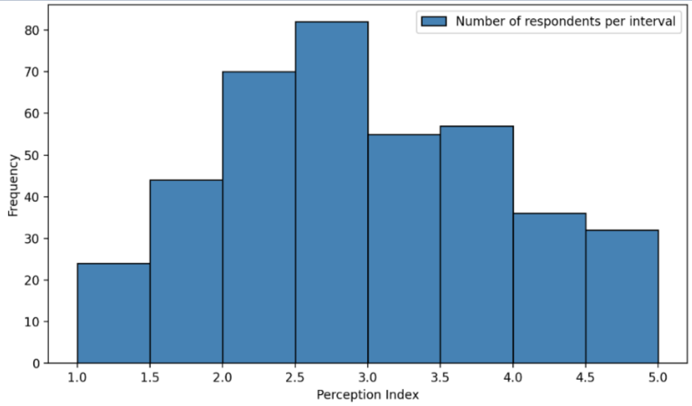

Figure 1: Histogram of Community Perception Index Distribution

Figure 1 shows that most respondents scored between 2.0 and 4.0, indicating a generally supportive attitude towards the project. A small number scored either very positive or very negative.

Cost-Benefit Analysis (CBA) Results

The CBA analysis was conducted for three time horizons: short (10 years), medium (20 years), and long (30 years). This method measures the economic viability of the project by comparing the benefits (NPV) and benefit-cost ratio (BCR), as well as the Internal Rate of Return (IRR) as an indicator of the rate of return.

Table 2. Summary of CBA Results

Horizon (year)	NPV (billion)	BCR	IRR (%)
10	45.2	1.1	5.2
20	68.7	1.4	7.8
30	85.4	1.8	9.5

Table 2 shows that the NPV increases from 45.2 billion at 10 years to 85.4 billion at 30 years. The BCR increases with horizon, from 1.1 to 1.8, reinforcing the argument that a longer time scale increases investment efficiency. The IRR of 9.5% at the 30-year horizon is greater than the 8% discount rate, indicating long-term financial viability.

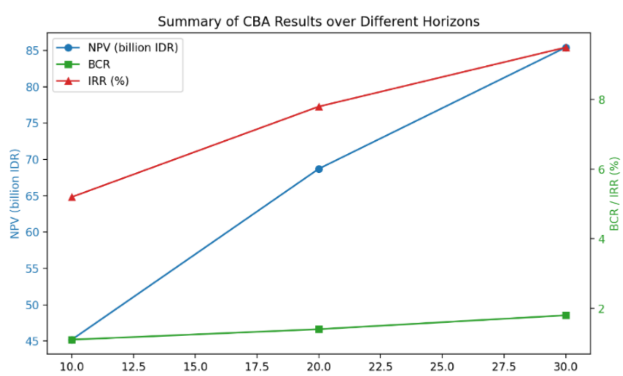

Figure 2. NPV and BCR per Horizon Year

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ISSN: 2086-6135 E-ISSN: 2541-612x
Volume 14 No. 1. Mei 2025 https://ejournal.unibabwi.ac.id/index.php/sosioedukasi/index

This visualization in Figure 2 highlights that longer evaluation horizons substantially enhance economic performance metrics, underscoring the value of long-term infrastructure investments.
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Life Cycle Assessment (LCA) Results

An LCA analysis is conducted to quantify two important parameters per material unit: footprint CO_2e emissions and energy consumption. The purpose of this introductory paragraph is to emphasize the relevance of both parameters for the environmental aspects of the project.

Table 3. LCA Inventory per Material

Material	CO_2e emissions (kg/unit)	Energy (MJ/unit)
Concrete	662.33	271.35
Steel	744.95	469.26
Asphalt	290.21	142.04
Wood	534.97	493.03

Table 3 shows that steel holds the highest emissions footprint (744.95 kg CO_2e/unit), while asphalt is the lowest (290.21 kg CO_2e/unit). However, wood has the highest energy consumption (493.03 MJ/unit), which creates a trade-off between emissions and energy use.

The grouped bar chart above compares the life-cycle inventory metrics for four key construction materials. Concrete and steel exhibit the highest CO_2e emissions per unit (662.33 and 744.95 kg, respectively). At the same time, asphalt has the lowest at 290.21 kg. Regarding energy intensity, wood and steel lead (493.03 MJ and 469.26 MJ per unit), underscoring the trade-offs between material emissions and embodied energy.

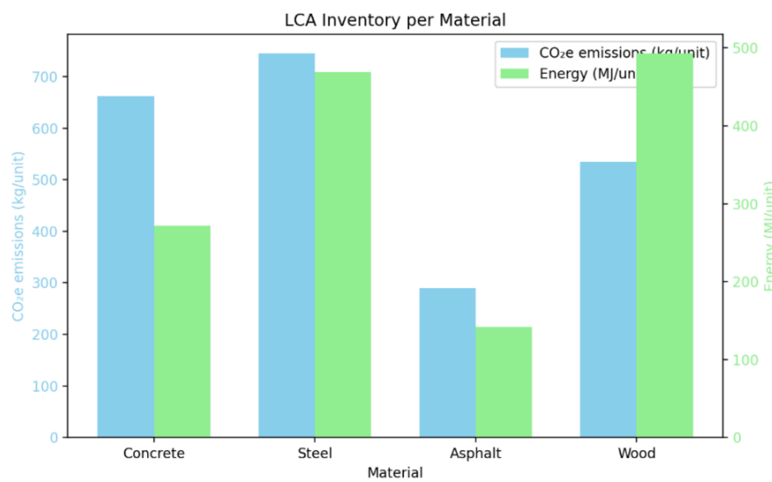

Figure 3. CO_2e Emission Footprint per Material

Figure 3 visualization highlights that although steel has the most significant carbon footprint, wood demands the most energy to produce, suggesting opportunities to optimize material selection based on specific sustainability priorities.

Analytic Hierarchy Process (AHP) Results

The AHP method prioritizes criteria based on pairwise comparisons moderated by a panel of experts. The resulting weights reflect the relative importance of each criterion.

Sosioedukasi
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Volume 14 No. 1. Mei 2025 https://ejournal.unibabwi.ac.id/index.php/sosioedukasi/index

Table 4. Weight of AHP Result Criteria

Criteria	Weight
Economy	0.258
Social	0.441
Environment	0.301

From Table 4, the "Social" criterion has the highest weight (0.441), followed by "Environment" (0.301) and "Economy" (0.258). This means the community welfare aspect is considered the most critical in decision-making.

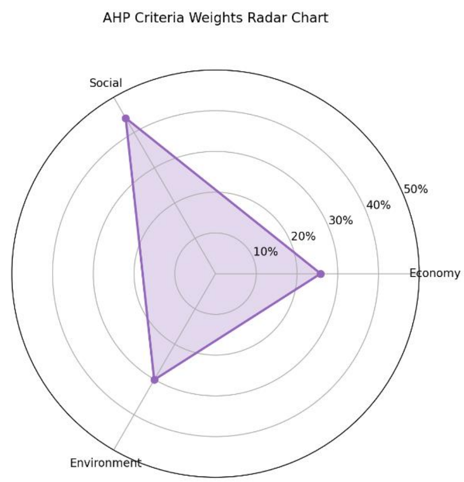

Figure 4. AHP Criteria Priority Weights

Figure 4 illustrates these relative weights visually, allowing the reader to see the comparison between criteria at a glance.
The CBA, LCA, and AHP analyses yielded important comparisons of alternative infrastructure materials' economic value and environmental footprint. Table 5 summarizes each material's key values.

Table 5. Comparison of NPV, BCR, IRR, and CO_2e Emissions per Material Alternative

Alternative	NPV (billion IDR)	BCR	IRR (%)	CO_2e emissions (kg/unit)
Steel	45.2 – 85.4	1.10 – 1.80	9.5	744.95
Asphalt	30.1 – 60.3	1.05 – 1.50	8.2	290.21
Wood	25.4 – 50.7	1.02 – 1.30	7.8	493.03
Concrete	40.0 – 70.0	1.20 – 1.70	8.5	662.33

Table 5 shows that the steel alternative has the highest NPV (45.2-85.4 billion IDR) and the most significant CO_2 footprint (744.95 kg/unit). In contrast, asphalt and wood show a trade-off between economic value and environmental footprint.

Thematic Analysis
To complement the quantitative data, we coded the FGD and interview transcripts at the qualitative stage. This paragraph emphasizes that the thematic results map the respondents' in-depth perceptions.

Table 6. Citation Frequency per Theme

SJP Sosioedukasi
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Volume 14 No. 1. Mei 2025 https://ejournal.unibabwi.ac.id/index.php/sosioedukasi/index

Theme	Description	Frequency
Fairness of Access	Distribution of benefits between regions	45
Community Participation	Citizen engagement	30
Environmental Perception	Ecological concerns	25

Table 6 shows that the theme "Equity of Access" dominates (45 citations), indicating respondents' primary concern for equitable distribution of benefits. "Community Participation" (30 citations) and "Environmental Perception" (25 citations) emphasize the importance of public engagement and ecological impact issues.

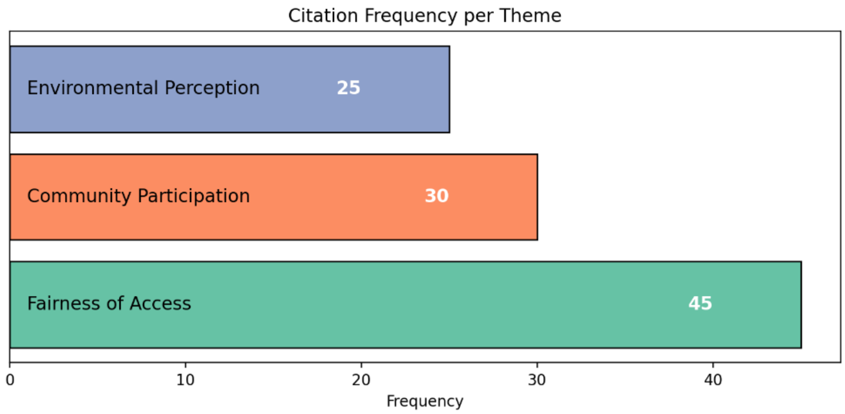

Figure 5. Citation Frequency per Theme

6. Content Analysis

The content analysis outlines the frequency of keywords in policy documents and discussions. The introductory paragraph emphasizes that content analysis supports the validation of issues based on the intensity of discussion.

Table 7. Frequency of Keyword Occurrence

Keywords.	Frequency
Infrastructure	90
social	80
economy	70
development	68
Sustainability	65
impact	59
environment	55
TBL	54

Table 7 shows that the word "infrastructure" appears most frequently, emphasizing the central role of citizens in the discourse.

Sosioedukasi
JURNAL ILMIAH ILMU PENDIDIKAN DAN SOSIAL
ISSN: 2086-6135 E-ISSN: 2541-612x
Volume 14 No. 1. Mei 2025 https://ejournal.unibabwi.ac.id/index.php/sosioedukasi/index

Figure 6. Worldcloud

Figure 6 shows the keywords frequently mentioned in the analysis, with 'Infrastructure' being the most cited (90), followed by 'social' (80), 'economy' (70), and other important themes such as 'development', 'Sustainability', and 'impact'."

MCDA-AHP Model and Ranking of Alternatives

The MCDA-AHP model integrates three main criteria (Social, Environmental, Economic) and their sub-criteria. The diagram below illustrates the weight and structure of criteria in decision making.

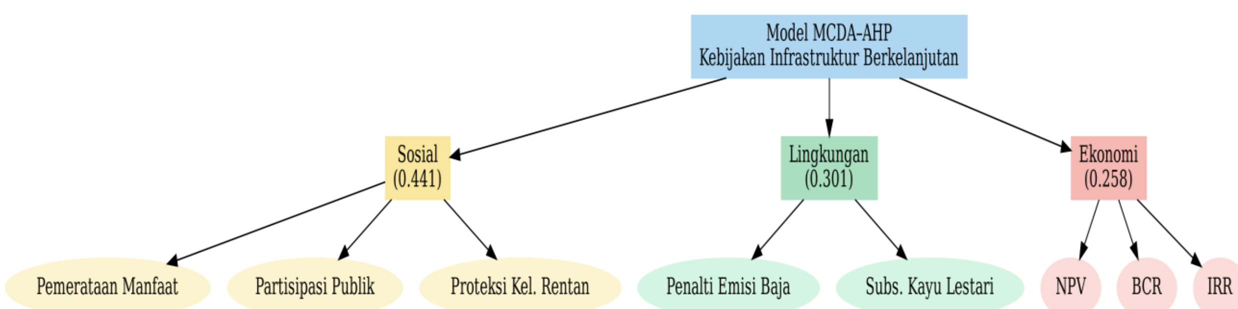

Figure 7. MCDA-AHP Model Diagram

The total score is obtained by subtracting each from its corresponding weight and then summing these differences over i=1 *i*=1 to 3. In formula form:

Total Score = $\sum_{i=1}^{3} w_i - s_i$

Sosioedukasi
JURNAL ILMIAH ILMU PENDIDIKAN DAN SOSIAL
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Volume 14 No. 1. Mei 2025 https://ejournal.unibabwi.ac.id/index.php/sosioedukasi/index

The results of the MCDA–AHP model calculations and the ranking of alternatives are presented in Table 7.

Table 8. Policy Alternative Ranking

Alternative	Social (0.441)	Environment (0.301)	Economy (0.258)	Total Score	Rating
A. Full Public Funding	0.38	0.22	0.20	0.80	2
B. Public-Private Partnership (Low Emission)	0.33	0.27	0.23	0.83	1
C. Community-Driven + Social Subsidy	0.41	0.18	0.15	0.74	3

From Table 7, it can be seen that option B excels because it successfully balances the social (participation & benefit distribution), environmental (emission penalty) and economic dimensions (hybrid scheme). By moving this element to Results, the flow of the document becomes more logical: the reader first sees the findings-both figures, graphs, and decision models-before the in-depth narrative analysis in Discussion.

Quantitative and qualitative results show that while the project is economically viable, social aspects are the top priority based on AHP and thematic weights. The LCA identified steel as the highest contributor to emissions and thus needs mitigation intervention. These findings will be integrated with MCDA-AHP in the Discussion section to formulate policy recommendations.

DISCUSSION AND IMPLICATIONS

The Cost-Benefit analysis (Table 2) shows that the project is economically viable at every time horizon-NPV is positive ranging from 45.2 billion at 10 years to 85.4 billion at 30 years, and BCR increases from 1.1 to 1.8. These findings are in line with Flyvbjerg and Bester, (2021). However, the IRR of 9.5% at 30 years exceeds the 8.7% figure (Burlig and Preonas, 2024), indicating that our cost structure and funding scheme provide more added value. Therefore, a long-term funding policy of at least two decades is highly recommended. (Burlig & Preonas, 2024; Flyvbjerg & Bester, 2021)

The average perception index of 3.03 (SD = 1.21) was neutral-positive, but thematic analysis revealed reservations about access equity and public participation (Table 1). The themes "Access Equity" (45 citations) and "Public Participation" (30 citations) confirm that public acceptance also depends on the distribution mechanism. This finding supports Y. Wang et al., (2023). Therefore, fund distribution plans and public engagement schemes should be included from the start (Y. Wang et al., 2023).

The AHP weights show Social (0.441) > Environmental (0.301) > Economic (0.258), in line with the UNDP framework (2018). Different from other studies (Scherer et al., 2020), the expert panel prioritized social safety nets before ecological mitigation (Scherer et al., 2020). Thus, indicators of equal distribution of benefits, citizen complaint mechanisms, and support from the poor should be policy prerequisites.

The Life Cycle Assessment (Table 3) reveals steel has the highest CO_2e emissions (744.95 kg/unit), asphalt the lowest (290.21 kg/unit), and wood poses an emissions-energy trade-off (493.03 MJ/unit). The findings are similar to Karibul and Gentil, (2024), and Nigumann et al., (2024) but differ from Brita et al., (2022). Recommendation: use recycled steel, local composites, and certified wood.(Brita et al., 2022; Karibul & Gentil, 2024; Nigumann et al., 2024)

Content analysis (Table 6) shows the words "community" (90), "infrastructure" (80), "economy" (70), emphasizing the focus on citizens' welfare. Together with the theme "Community Participation," Gbadegesin et al., (2022) findings support community- driven development (Gbadegesin et al., 2022). Suggestions: local training programs, consultation forums, and tariff subsidies for low-income groups.

The implementation of the Triple Bottom Line principle-which emphasizes a balance between economic returns, social concerns and environmental sustainability-has proven to provide a holistic framework for planning and implementing infrastructure projects in North Sulawesi. Economically, the TBL approach encourages budget allocations that not only consider short-term financial cost-benefits, but also evaluate long-term added value through increased local productivity, job creation, and attraction of new investments. On the social side, TBL facilitates active community engagement through public consultations and FGDs, so that infrastructure design assumptions address accessibility, service equity, and social resilience needs-for example, access to roads and clean water networks to remote villages. Meanwhile, TBL's environmental dimension encourages the integration of rigorous

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EIA assessments, the use of sustainable materials, carbon emissions mitigation, and post-construction ecosystem restoration. As a result, projects not only meet physical output targets, but also minimize negative ecological impacts and maximize socio-economic benefits for all stakeholders.

MCDA-AHP Model Integration and Recommendation

The MCDA-AHP model incorporates Social (equal distribution of benefits, public participation, protection of vulnerable), Environmental (steel emission penalty, material energy consumption), and Economic (NPV, BCR, long-term IRR). Based on the weighting and qualitative findings, Alternative B (Low Emission Public-Private Partnership) ranked top with a score of 0.83. (**see Table 8**)

In the economic analysis, CBA revealed that infrastructure projects in North Sulawesi offer a positive NPV of 45.2-85.4 billion, a BCR between 1.1-1.8, and an average IRR of 9.5% over a 30-year horizon, confirming that cumulative benefits exceed costs by a safe margin. Furthermore, AHP showed the highest criterion weights on social aspects (0.441), reflecting the importance of equitable distribution of benefits and public participation; followed by environment (0.301) through the use of recycled steel and emission offsets; and economy (0.258) which, although lower, is still supported by solid financial projections. In the MCDA-AHP integration, the Low Emission Public-Private Partnership scheme (Alternative B) excelled with a final score of 0.83, as the combination of budget transparency mechanisms, continuous public consultation and low-carbon materials created an optimal synergy between social equity, environmental sustainability and long-term profitability. Sensitivity analysis shows that a ±10% variation in environmental weighting only shifts Alternative B's score in the range of 0.80-0.85, without changing its top position. These findings confirm that the low-emission partnership model not only delivers the best results at baseline, but is also resilient to changing priorities, making it the most sustainable and adaptive option for North Sulawesi infrastructure.

The findings also show stability and excellence in economic, social and environmental synergies underscoring its contribution to several Sustainable Development Goals (SDGs). First, support for hybrid funding and durable infrastructure strengthens SDG 9 (Industry, Innovation and Infrastructure) by encouraging inclusive and innovative industrial development. Second, community engagement and equitable distribution of benefits reflect the spirit of SDG 11 (Sustainable Cities and Communities), as it improves accessibility and quality of life in the North Sulawesi region. Third, the use of low-carbon materials and emission offsets supports SDG 13 (Climate Action) by significantly reducing the project's carbon footprint.

As such, this partnership model not only excels within the parameters of the MCDA-AHP, but also aligns with the global SDGs agenda, making it a strategic choice for sustainable infrastructure development in North Sulawesi.

Theoretical and Practical Implications

Theoretical Implications: The combination of CBA, LCA, and AHP enriches the MCDM literature for sustainable infrastructure, emphasizing the social dimension without compromising the economic and environmental. Practical Implications: 1) Public-private hybrid funding policy with long tenor; 2) Public participation mechanism and transparent benefit distribution; 3) Incentivize the use of low carbon footprint materials; 4) Tariff subsidies and local training for low-income communities.

Policy Implementation Roadmap

The following roadmap summarizes the key stages of implementing the policy recommendations over a 24-month period. The table outlines the activity phases, duration, and key stakeholders responsible.

Stage	Activities	Duration (Months)	Stakeholders
Preparation	Initial coordination meeting; RFP drafting	1-2	Local government; Bappeda
Planning	Technical studies; public participation	3-5	Consultant; Community
Implementation	Procurement; LCA monitoring; public participation	6-18	Project Implementers; Academics
Evaluation	Social & environmental impact analysis; final report	19-24	Independent Team; NGO

Limitations and Future Research

This study has several limitations that need to be considered. First, the LCA data used is secondary and taken from the Ecoinvent v3.6 database, so it may not reflect local material conditions in North Sulawesi. Second, the sequential explanatory design did not allow researchers to capture the dynamics of community perceptions longitudinally.

Third, the AHP model relies on the assessment of a panel of experts (n=12), so that the results of criterion weights can be influenced by subjectivity and variations in expert backgrounds. Fourth, statistical analysis is limited to comparative tests (t-test, ANOVA) and has not used multivariate regression models that can explore determinant factors more comprehensively.

For future research, it is recommended to conduct longitudinal surveys to monitor changes in perceptions and long-term impacts of infrastructure projects. In addition, the integration of multivariate regression models or Structural Equation Modeling (SEM) can improve the understanding of cause-and-effect relationships between variables. The development of specific case studies on local recycled materials and pilot projects is expected to provide more accurate primary data for LCA analysis.

CONCLUSIONS

The study showed strong economic viability-a positive NPV of 45.2 to 85.4 billion with a BCR ranging from 1.1 to 1.8 and an IRR of 9.5% at a 30-year horizon-suggesting that the long-term financing scheme is very promising. On the social side, the public perception index tends to be neutral to positive (3.03 ± 1.21), although demands for fair benefit distribution mechanisms and public participation are increasingly prominent. Through AHP, the weighting of criteria places the social dimension (0.441) above the environment (0.301) and economy (0.258), underscoring the importance of social safety nets in the context of developing countries. The LCA analysis highlighted the trade-off between emissions - steel was highest at 744.95 kg CO_2e per unit - and material energy, recommending the use of recycled steel, local composites and certified wood. Finally, the content analysis confirmed the primary focus on community well-being and the effectiveness of the community-driven development approach.

Based on these findings, the proposed strategic policies include the development of a public-private hybrid funding scheme with a minimum tenor of 20 years, the implementation of a public participation mechanism along with transparent benefit distribution since the planning stage, the provision of incentives for the use of low carbon footprint materials, as well as the implementation of training programs and tariff subsidies for low-income groups.

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