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CASE STUDY

Managing Cost-Overrun Risks in Maritime Hinterland Infrastructure

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ABSTRACT
This study investigates cost-overrun risks in maritime hinterland infrastructure, addressing the limited integration of causal diagnosis, risk prioritisation, and consequence assessment in infrastructure project governance. Focusing on the Serbelawan–Pematang Siantar Toll Road in Indonesia, the study employs a mixed-method case study using project documentation, semi-structured interviews, and assessments from four subject matter experts. Root Cause Analysis (RCA), the Analytical Hierarchy Process (AHP), and semi-quantitative Event Tree Analysis (ETA) are applied sequentially to identify underlying risk factors, prioritise mitigation strategies, and examine potential consequence pathways. The findings identify land-acquisition prevention as the highest-priority category (AHP weight = 0.468), followed by design-change prevention (0.250) and contractual risk management (0.138). The leading mitigation strategies are cross-agency coordination (0.279), comprehensive detailed engineering design (0.168), and pre-contract site assessment (0.091). The analysis highlights how institutional coordination failures, inadequate project preparation, and contractual weaknesses contribute to interconnected cost and schedule risks. The study's originality lies in applying an integrated RCA–AHP–ETA framework to infrastructure supporting maritime hinterland connectivity, linking risk origins, preventive priorities, and qualitative consequence pathways. It provides project-level insights for strengthening front-end governance and infrastructure delivery reliability in emerging maritime economies. However, the findings remain context-specific and do not establish direct effects on maritime logistics performance.

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1. INTRODUCTION

Maritime connectivity is a critical determinant of trade integration, logistics efficiency, and regional economic development, particularly in archipelagic and emerging economies. The economic function of seaports extends beyond port boundaries because port performance depends on the reliability of hinterland transport networks connecting maritime gateways with industrial areas, logistics centres, production zones, and inland markets. Improvements in maritime connectivity can generate sustained regional economic benefits, while transport infrastructure expansion represents an important channel through which such benefits are realised (Li et al., 2023). Port–hinterland connectivity is therefore increasingly understood as a multidimensional network involving direct and indirect relationships among ports, transport modes, and

inland logistics nodes rather than merely as a road-to-port connection (Deshmukh & Song, 2024). This perspective is particularly relevant to Indonesia, where the integration of ports and inland production centres is essential for reducing logistics frictions and supporting regional economic activity. The Serbelawan–Pematang Siantar Toll Road, as part of the wider Kuala Tanjung–Tebing Tinggi–Parapat corridor, provides an appropriate setting for examining such maritime hinterland infrastructure because the project supports regional accessibility and the movement of goods and passengers across North Sumatra.

The expected economic benefits of hinterland infrastructure, however, depend substantially on whether projects can be delivered within acceptable cost and schedule parameters. Cost overruns in highway and toll-road projects are rarely attributable to a single cause; instead, they emerge from combinations of financial constraints, weak planning, design and scope changes, land-acquisition problems, material shortages, contractor-related weaknesses, regulatory uncertainty, and external conditions (Atapattu et al., 2023; Habibi & Kermanshachi, 2018; Mahmud et al., 2021; Sharma et al., 2021; Zhasmukhambetova et al., 2025). A recent systematic review confirms that these categories recur across highway projects internationally, indicating that cost escalation is fundamentally multidimensional (Zhasmukhambetova et al., 2025). Indonesian evidence shows a similar pattern: cost-overrun risks cluster around design and scope changes, land-acquisition delays, financial constraints, contractor weakness, procurement difficulties, and material-price volatility. Evidence from 70 Indonesian toll-road projects further demonstrates that contract changes are associated with substantially higher cost-overrun rates, strengthening the argument that cost performance reflects governance and contract-management processes rather than merely inaccurate initial estimates (Wibowo & Santoso, 2024).

Design changes, land acquisition, financing, and procurement are particularly important because they affect project costs through different transmission mechanisms. Design and contract changes tend to produce direct budget growth through additional quantities, rework, and change orders, whereas land-acquisition problems frequently affect costs indirectly through delayed access, schedule extension, financing disruption, and prolonged overhead (Sihombing, 2017; Sihombing et al., 2018; Wibowo & Santoso, 2024). The evidence synthesis for Indonesian toll roads identifies design and contract changes as among the clearest direct cost-escalation mechanisms while showing that land acquisition frequently operates through delay and financing channels. Contractor administration and procurement add further exposure through delayed payments, weak coordination, poor monitoring, inadequate tender documentation, material shortages, and price fluctuations (Mohamed et al., 2019; Rani et al., 2025; Yosritzal et al., 2019). Cost and schedule performance are also closely coupled, because prolonged duration increases labour, equipment, supervision, administrative, and financing costs while extending exposure to inflation and market uncertainty (Belay et al., 2021; Jadhav & Katdare, 2026; Muchhara & Dhungana, 2025). The Serbelawan–Pematang Siantar

project reflects these same patterns through land-acquisition delays, design changes, material-price escalation, logistics disruption, and project-duration extension.

Despite this growing literature, two gaps remain. First, cost-overrun research is still predominantly framed within construction and project management, whereas maritime-economics research focuses on port connectivity, regional accessibility, and the efficiency of hinterland logistics systems (Deshmukh & Song, 2024; Li et al., 2023). The intersection between these streams remains underdeveloped, particularly for land-based infrastructure whose wider function is to support maritime gateways. Second, prior studies often analyse risk identification, prioritisation, mitigation, or consequence modelling separately. Indonesian and international studies have employed AHP, FMEA, Monte Carlo simulation, probability-impact analysis, risk mapping, and hybrid assessment techniques (Aslam & Baffoe-Twum, 2024; Karimi Azeri et al., 2011; Pratama et al., 2023; Ronyastra et al., 2024; Sari et al., 2024), yet evidence remains limited on frameworks that sequentially integrate root-cause diagnosis, priority setting, and consequence-pathway analysis. Governance research also indicates that contractual design, project preparation, monitoring, audit mechanisms, and risk allocation can materially influence toll-road performance (Wibowo & Alfen, 2015; Winata & Gultom, 2024; Wirahadikusumah et al., 2018). Risk-based toll-road studies further demonstrate that structured mitigation strategies can reduce projected cost exposure, although evidence on realised post-mitigation performance remains comparatively limited (Isvara et al., 2023; Sandhyavitri et al., 2017).

To address these gaps, this study examines cost-overrun risk management in the Serbelawan–Pematang Siantar Toll Road as a case of maritime hinterland infrastructure in Indonesia. It integrates Root Cause Analysis (RCA), the Analytical Hierarchy Process (AHP), and Event Tree Analysis (ETA) to connect causal diagnosis, risk prioritisation, and consequence evaluation. The study addresses three questions: (1) What are the dominant cost-overrun risks affecting the Serbelawan–Pematang Siantar Toll Road as maritime hinterland infrastructure? (2) What underlying causes and risk pathways explain the emergence and consequences of these risks? (3) Which mitigation strategies should be prioritised to improve cost reliability and support timely infrastructure delivery? The study contributes by linking toll-road risk management with maritime hinterland infrastructure, by integrating RCA–AHP–ETA within a single sequential framework, and by providing practical implications for contractors, infrastructure owners, regulators, and policymakers responsible for port-connected transport corridors. This positioning is consistent with recent evidence that future toll-road cost control should emphasise design maturity, land-readiness gating, strict change-order governance, integrated schedule-cost-procurement monitoring, and governance structures that strengthen preparation and monitoring incentives.

The combination of RCA, AHP, and ETA is not new in itself; Shih et al. (2016) previously applied these three methods sequentially to a different engineering context. The contribution of this study is therefore not the methodological combination per se, but its case-specific application: the integration of RCA–AHP–ETA within a single sequential

framework for an Indonesian toll-road project situated in a maritime hinterland setting, and the way the study traces how land, design, procurement, contractual, and governance-related risks connect to one another within that project. The study is deliberately scoped at the level of project delivery: it examines how cost and schedule risks may affect the delivery of infrastructure that supports a maritime corridor, and it does not measure port throughput, freight cost, shipping activity, or logistics performance directly, so no claim is made that the findings demonstrate an improvement in maritime logistics outcomes.

2. LITERATURE REVIEW

2.1 Maritime Hinterland Infrastructure and Economic Connectivity

Maritime hinterland infrastructure refers to the land-based transport systems that connect seaports with industrial areas, logistics centres, production zones, and inland markets. Its economic relevance arises because port performance depends not only on maritime capacity but also on the reliability of inland transport links. Stronger maritime connectivity can stimulate regional economic activity, while transport infrastructure expansion represents one mechanism through which those benefits are transmitted to surrounding economies (Li et al., 2023). Port–hinterland connectivity should therefore be understood as part of a broader logistics network in which roads, logistics nodes, industrial locations, and maritime gateways interact rather than operate independently.

For emerging maritime economies, the quality of hinterland access can influence freight mobility, regional integration, and the effectiveness of infrastructure investment. This is particularly relevant in Indonesia, where the integration of inland economic centres with port gateways is essential for reducing logistical fragmentation. The Serbelawan–Pematang Siantar Toll Road forms part of the broader Kuala Tanjung–Tebing Tinggi–Parapat corridor and thus provides a relevant case of land-based infrastructure supporting a wider maritime logistics system. The economic significance of such infrastructure is therefore not confined to road mobility; it also lies in its capacity to support the timely movement of goods and improve access between inland economic activity and maritime gateways.

The broader literature suggests that the value of port connectivity depends on whether complementary infrastructure is delivered reliably. Li et al. (2023) found that improvements in maritime connectivity had a durable positive effect on regional economic growth and identified port infrastructure expansion as one channel through which this effect is realised. This implies that delays, cost escalation, or governance failures in supporting hinterland infrastructure may weaken the expected economic benefits of maritime connectivity. Accordingly, cost and schedule reliability should be treated as part of the economic performance of maritime hinterland infrastructure rather than as purely internal construction concerns.

2.2 Cost-Overrun Risks in Transport Infrastructure

Cost overruns remain one of the most persistent problems in large transportation infrastructure projects. Recent highway research identifies financial constraints, regulatory uncertainty, land acquisition, design and scope changes, procurement weaknesses, contractor-related problems, planning deficiencies, material shortages, and environmental conditions as recurring determinants of cost and schedule performance (Zhasmukhambetova et al., 2025). The evidence synthesis used in this study reports a similar pattern across Indonesian toll-road and highway projects, where risks cluster around design or scope changes, land-acquisition delays, financial constraints, contractor weakness, and procurement or material-related problems.

Among these factors, design changes and contract changes appear to be particularly strong direct drivers of cost escalation. Wibowo and Santoso (2024), using evidence from 70 Indonesian toll-road projects, found that projects experiencing contract changes had materially higher cost-overrun rates than the overall sample. More recent evidence from Sasmito and Amin (2026) strengthens this finding. Their study of 20 Indonesian toll-road projects found that poor planning, technical design changes, discrepancies between design and site conditions, land-acquisition delays, and inadequate stakeholder coordination explained 94.5% of change-order variation. Change orders, in turn, explained 94.9% of cost-overrun variation and 93.6% of time-overrun variation. Design changes had the strongest effect on cost, whereas land-acquisition delays had the strongest effect on time. Garuda Kemdiktisaintek

This evidence is consistent with the synthesis contained in the evidence synthesis used in this study, which identifies design and contract changes as the clearest direct mechanisms of cost escalation in Indonesian toll-road projects. The same review distinguishes land acquisition from design changes because land risks often influence costs indirectly through delayed work access, financing blockage, prolonged overhead, and schedule disruption rather than through immediate budget growth. Earlier Indonesian financing studies also highlight the role of land readiness, borrowing conditions, and financing uncertainty in toll-road delivery (Sihombing, 2017; Sihombing et al., 2018).

The interaction between schedule and cost further complicates project performance. Schedule delays can prolong labour, equipment, supervision, and administrative expenditure while increasing exposure to inflation, market uncertainty, and supply-chain disruptions (Belay et al., 2021; Muchhara & Dhungana, 2025; Jadhav & Katdare, 2026). The evidence synthesis consequently treats time and cost overruns as tightly coupled rather than independent phenomena. This relationship is especially relevant for toll-road projects because delayed land access, weak coordination, procurement disruption, and late decisions may initially appear to be schedule issues but later become major cost drivers.

2.3 Governance, Procurement, and Risk-Transmission Mechanisms

Transport-project cost overruns are also shaped by governance and contractual arrangements. Weak contract administration, delayed payments, poor coordination, and inadequate monitoring are repeatedly associated with adverse project outcomes, while procurement weaknesses such as poor tender documentation, material shortages, and price fluctuations contribute directly to cost escalation (Mohamed et al., 2019; Mahmud et al., 2021; Rani et al., 2025; Yosritzal et al., 2019). These findings indicate that cost performance cannot be separated from organisational capability and governance quality.

Contract form and governance design are particularly important in infrastructure projects involving multiple public and private stakeholders. Winata and Gultom (2024) show that governance arrangements in Indonesian PPP toll roads influence cost and completion performance, particularly through differences in project preparation, monitoring, audit mechanisms, and incentive structures. The evidence synthesis likewise concludes that project-level controls should be complemented by procurement and contract-structure choices. Earlier PPP research also highlights the importance of government support, risk allocation, and contingent-liability management in toll-road infrastructure (Wibowo & Alfen, 2015; Wirahadikusumah et al., 2018).

Procurement and supply-chain risks form another important transmission mechanism. Material shortages, delivery delays, and price volatility can generate both direct cost growth and schedule slippage. The literature therefore supports earlier supplier qualification, more rigorous procurement planning, stronger contractor selection, improved payment controls, and integrated monitoring of procurement and schedule performance (Atapattu et al., 2023; Rani et al., 2025; Yosritzal et al., 2019). The evidence synthesis used in this study also suggests that toll-road cost control should be organised around design maturity, land-readiness gating, strict change-order governance, integrated schedule-cost-procurement monitoring, and contract forms that strengthen preparation and monitoring incentives.

These mechanisms are directly relevant to the prevention framework used in the Serbelawan–Pematang Siantar case. Political prevention focuses on land acquisition and inter-agency coordination; technical prevention addresses detailed engineering design and change control; project-resource prevention targets escalation clauses, bulk purchasing, long-term supplier contracts, and contingency budgeting; environmental prevention addresses weather-related risks; and managerial prevention emphasises pre-contract site assessment, performance-based clauses, and joint vendor risk review. This structure is consistent with the wider literature showing that cost overruns emerge through interactions among institutional, technical, market, environmental, and managerial risks rather than from a single isolated failure.

2.4 Integrated Risk Assessment and Analytical Approaches

Infrastructure risk studies employ a wide range of analytical methods, including AHP, FMEA, Monte Carlo simulation, probability-impact assessment, GIS-based risk mapping, DEMATEL, and other hybrid approaches. The evidence base cited in the evidence

synthesis used in this study includes applications of AHP and benefit-cost analysis (Azis, 1990), Monte Carlo financial risk analysis (Ronyastra et al., 2024), hybrid Rough Delphi–Rough DEMATEL for toll-road operations (Pratama et al., 2023), and other structured risk-assessment techniques.

AHP is particularly useful when decision-makers must prioritise multiple criteria and mitigation alternatives under uncertainty. It allows expert judgments to be converted into relative weights, thereby supporting structured comparison among competing risks and responses. Root Cause Analysis (RCA), by contrast, focuses on identifying the underlying mechanisms responsible for observed problems rather than merely ranking their surface manifestations. Event Tree Analysis (ETA) provides a complementary forward-looking approach by examining alternative consequence pathways following an initiating event and evaluating the success or failure of control measures.

The use of these methods in combination has conceptual advantages. RCA can answer why a risk occurs, AHP can determine which risks and mitigation measures deserve priority, and ETA can evaluate how alternative controls alter potential outcomes. This sequential logic provides a more comprehensive basis for decision-making than the independent application of a single technique. The evidence synthesis used in this study notes that available road and toll-road studies apply AHP, FMEA, Monte Carlo simulation, probability-impact approaches, and structured risk mapping, but the evidence remains uneven and fragmented across methods.

This fragmentation is important because toll-road cost overruns involve multiple interacting mechanisms. Design changes can cause direct budget growth, land acquisition can transmit costs through schedule and financing channels, and procurement or contractor weaknesses can create both direct and indirect effects. The evidence synthesis therefore distinguishes three pathways: direct budget-growth risks, cost-of-delay risks, and financing and governance transmission risks. An integrated RCA–AHP–ETA framework is particularly suitable for this structure because it links causal mechanisms, priority assessment, and consequence evaluation within one analytical sequence.

2.5 Research Gap and Conceptual Positioning

Two major gaps emerge from the literature. The first is substantive. Existing cost-overrun research largely treats toll-road risk as a construction-management issue, whereas maritime economics focuses on port connectivity, regional growth, and hinterland logistics. Li et al. (2023), for example, provide evidence that improved maritime connectivity can stimulate regional economic growth, while Indonesian toll-road studies concentrate primarily on project cost, design, land acquisition, governance, and contract performance (Sasmito & Amin, 2026; Wibowo & Santoso, 2024). The relationship between these research streams remains insufficiently developed, particularly for toll roads that support the broader functioning of maritime logistics corridors.

The second gap is methodological. Previous studies frequently identify cost-overrun determinants, assess individual risks, or evaluate mitigation strategies

separately. Although hybrid risk-analysis methods are increasingly used, relatively few studies integrate root-cause diagnosis, multi-criteria prioritisation, and consequence-pathway analysis in a single sequential framework. The evidence synthesis used in this study explicitly notes the uneven integration of AHP, FMEA, Monte Carlo simulation, and related approaches across toll-road studies.

This study addresses both gaps by applying an integrated RCA–AHP–ETA framework to the Serbelawan–Pematang Siantar Toll Road as a case of maritime hinterland infrastructure. Conceptually, the study assumes that institutional and governance risks, technical and design risks, procurement and market risks, and environmental and managerial risks can generate cost and schedule disruptions through direct, delay-related, or financing-related pathways. The integrated framework is then used to identify root causes, prioritise mitigation options, and evaluate consequence pathways. This positioning extends cost-overrun analysis beyond construction performance alone and links project-risk governance to the reliable delivery of infrastructure supporting maritime connectivity.

3. METHODOLOGY

This study employed a mixed-method case study design to examine cost-overrun risks in the Serbelawan–Pematang Siantar Toll Road Project. Primary data were collected through semi-structured interviews and expert-judgement questionnaires involving four Subject Matter Experts (SMEs) with project-specific managerial and technical knowledge, while secondary data were obtained from project documents, including contract agreements, contract amendments, project schedules, and progress reports. The use of expert judgement is appropriate in infrastructure-risk assessment where project-specific data are incomplete or uncertainty must be assessed using specialist knowledge (Mottahedi et al., 2021). The analytical process was conducted sequentially using Root Cause Analysis (RCA), the Analytical Hierarchy Process (AHP), and Event Tree Analysis (ETA). RCA was applied through Fishbone Diagram categorisation and the 5 Whys technique to identify underlying causes of dominant cost-overrun risks. AHP was subsequently used to prioritise risk categories and mitigation alternatives through pairwise comparisons based on Saaty's 1–9 scale. AHP is specifically designed to convert expert pairwise judgments into relative priority scales for complex multi-criteria decisions (Saaty, 2008). Priority weights were derived through eigenvector analysis, and judgement consistency was assessed using a Consistency Ratio threshold of $CR < 0.10$, as specified in the original analytical procedure. The four-member expert panel was purposively selected for direct, project-specific expertise on the Serbelawan-Pematang Siantar Toll Road, representing distinct stakeholder perspectives (owner, contractor, consultant, and/or regulator) so that pairwise judgments would reflect reasonably independent viewpoints on project risk. Table A1 reports each expert's role, organisation type, years of professional experience, project-specific involvement, relevant competence, and any potential conflict of interest

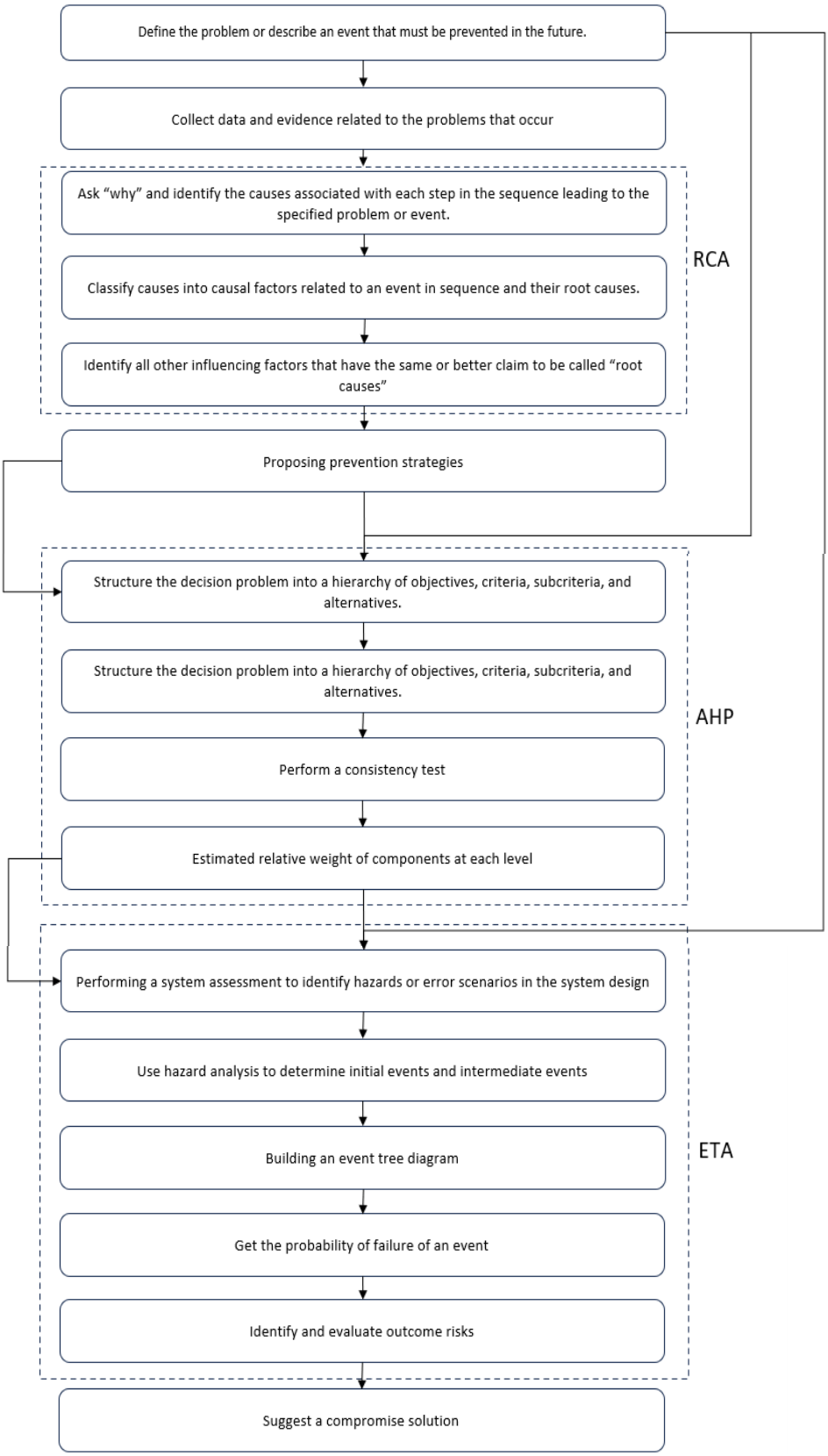


Figure 1. Research Design

Event Tree Analysis (ETA) was used to evaluate, for the highest AHP-priority risk pathways, how the sequence of initiating events and candidate pivotal controls could

lead to outcomes of differing severity. In its original quantitative form, ETA requires branch probabilities - the empirical or elicited likelihood that each control succeeds or fails - estimated independently from historical project data or a structured probability-elicitation procedure. Because this study's four-SME dataset was designed to elicit AHP preference weights rather than control-reliability probabilities, AHP priority weights were not treated as ETA branch probabilities. Instead, ETA was applied here in a semi-quantitative, consequence-oriented form: the branch structure of each event tree reflects the AHP-derived order and relative emphasis of pivotal controls, while the terminal outcome of each pathway is expressed as a qualitative severity category - Low, Moderate, or High - rather than as a derived numerical probability of cost overrun. These severity categories are defined operationally in terms of combined cost-and-schedule impact: High (Tinggi) indicates major budget growth and/or schedule delay exceeding several months, typically arising when all pivotal controls in the pathway fail or are only partially implemented; Moderate (Sedang) indicates measurable but contained cost and/or schedule impact, typically arising when some but not all pivotal controls are effectively implemented; and Low (Rendah) indicates minimal cost or schedule impact, typically arising when the relevant pivotal controls are successfully implemented. The numerical values shown at each branch point in the event-tree figures represent the relative emphasis assigned to each pivotal control on the basis of its AHP-derived priority and expert assessment of its likely effectiveness, and should be read as an ordinal indication of which control combinations are judged most consequential for outcome severity, not as calibrated probabilities of control success or failure. The sequential use of RCA, AHP, and semi-quantitative ETA is methodologically consistent with Shih et al. (2016), who applied these three methods sequentially in a different engineering context: RCA identifies root causes and feasible prevention strategies, AHP prioritises those strategies, and ETA illustrates, in ordinal terms, how the effectiveness of controls plausibly shapes the severity of downstream consequences. The project results indicate that effective control implementation was associated with lower-severity cost and schedule consequences, whereas unsuccessful controls were associated with higher-severity cost-overrun outcomes.

4. RESULTS

4.1 Identification of Cost-Overrun Risks

The analysis identified five dominant risks contributing to cost overruns in the Serbelawan–Pematang Siantar Toll Road Project: land acquisition delays, design changes during construction, material price escalation, logistics and supply-chain disruptions, and project-duration extension. These risks were consistently identified through project documentation, interviews, and expert assessments. Land acquisition delays restricted access to construction work fronts and disrupted planned construction sequencing, while design modifications increased work quantities and resource requirements. Material-price escalation and logistics disruptions further increased

procurement uncertainty, particularly as the prolonged project duration exposed the project to inflation and market volatility.

The identified risks indicate that cost escalation resulted from interconnected institutional, technical, market, and managerial factors rather than a single project failure. This pattern is broadly consistent with Indonesian toll-road evidence showing that contract changes and government-related risks can materially influence cost-overrun performance (Wibowo & Santoso, 2024).

4.2 Root Cause Analysis

Root Cause Analysis was conducted using the Fishbone Diagram and the 5 Whys technique to determine the underlying causes of the dominant cost-overrun risks. The analysis grouped causal factors into major dimensions related to project implementation and demonstrated that cost overruns were associated not only with technical problems but also with weaknesses in project preparation, coordination, contractual management, and external conditions.

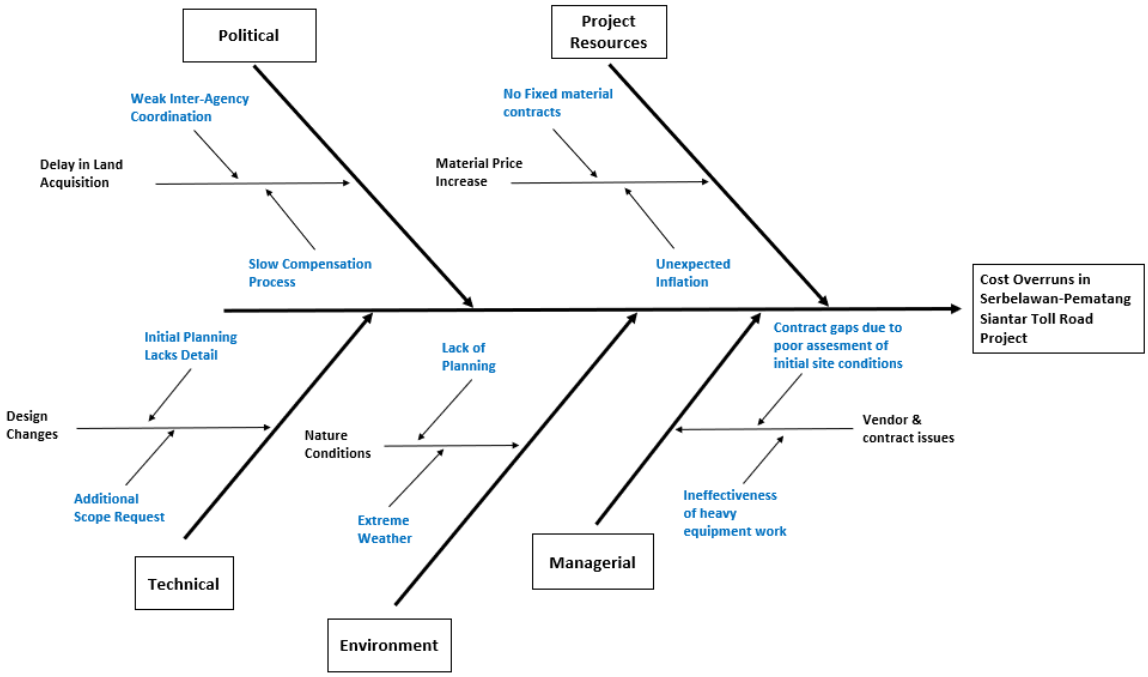


Figure 2. Fishbone diagram of cost overrun in Siantar Toll Road

Figure 3 illustrates the causal structure underlying project cost overruns. The analysis indicates that land-related constraints, design and technical issues, resource and procurement conditions, environmental uncertainty, and managerial or contractual weaknesses interact in generating cost escalation. The RCA results therefore suggest that observable cost deviations were symptoms of deeper deficiencies in early project readiness and coordination.

Based on the identified root causes, a set of preventive strategies was subsequently developed. These strategies addressed political and institutional coordination, technical

preparation, project resources, environmental uncertainty, and managerial or vendor-related risks.

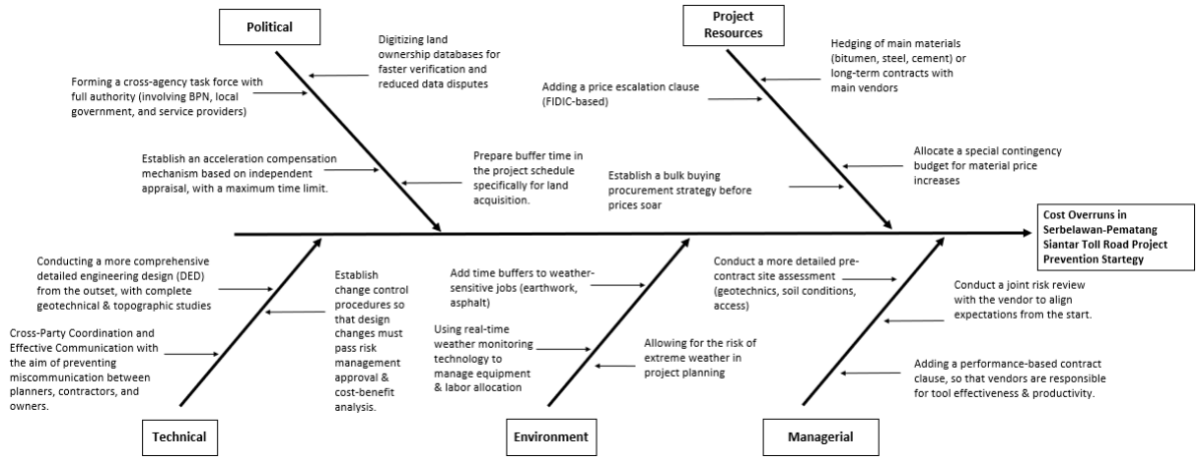


Figure 3. Fishbone diagram of cost overrun prevention strategies

Figure 3 presents the prevention strategies derived from the RCA stage. These alternatives provided the analytical basis for the subsequent AHP evaluation, in which experts compared the relative importance of prevention categories and specific mitigation measures.

4.3 Prioritisation of Mitigation Strategies Using AHP

Following RCA, AHP was applied to prioritise the identified prevention strategies using expert pairwise comparisons. The hierarchy consisted of five major prevention categories: land acquisition delay, design changes, material price increases, natural conditions, and vendor and contractual issues.

Table 1. Relative priorities of the selection criteria of the prevention strategies

Main Criterion	Local priority	Subcriterion	Local Priority	Global Priority	Rank
Political Prevention (Delay in Land Acquisition)	0.468	Establish a cross-agency task force with full authority (involving the National Land Agency (BPN), local governments, and service providers)	0.595	0.279	1
		Establish an accelerated compensation mechanism based on independent appraisals, with a maximum time limit	0.184	0.086	4
		Digitize the land ownership database to speed up verification and reduce data disputes	0.109	0.051	6
		Establish a buffer time in the project schedule specifically for land acquisition	0.112	0.052	5
Technical Prevention (Design Changes)	0.250	Conduct a more comprehensive detailed engineering design (DED) from the outset, with comprehensive geotechnical and topographic studies	0.670	0.168	2
		Effective cross-party coordination and communication to prevent miscommunication between planners, contractors, and owners	0.134	0.033	10
		Establish a change control procedure to ensure design changes are subject to risk management approval and cost-benefit analysis	0.196	0.049	7
	0.092	Add a price escalation clause (FIDIC-based)	0.425	0.039	8

Project Resources Prevention (Material Price Increase)		Establish a bulk purchasing procurement strategy before prices spike	0.103	0.010	16
		Hedge key materials (bitumen, steel, cement) or establish long-term contracts with key vendors	0.361	0.033	11
		Allocate a dedicated contingency budget for material price increases	0.111	0.010	15
Environment Prevention (Nature Conditions)	0.052	Add a time buffer for weather-sensitive projects (earthwork, asphalt)	0.576	0.029	12
		Use real-time weather monitoring technology to manage equipment and labor allocation	0.179	0.009	17
		Allow for extreme weather risks in project planning	0.244	0.013	13
Managerial Prevention (Vendor & Contract Issues)	0.138	Conduct a more detailed pre-contract site assessment (geotechnics, soil conditions, access)	0.662	0.091	3
		Add a performance-based contract clause to hold vendors accountable for equipment effectiveness and productivity	0.076	0.011	14
		Conduct a joint risk review with vendors to align expectations from the outset	0.262	0.036	9

As shown in Figure 4, each major criterion was linked to specific mitigation alternatives. Pairwise comparisons were conducted by the four SMEs using the AHP scale, and local and global priority weights were subsequently calculated.

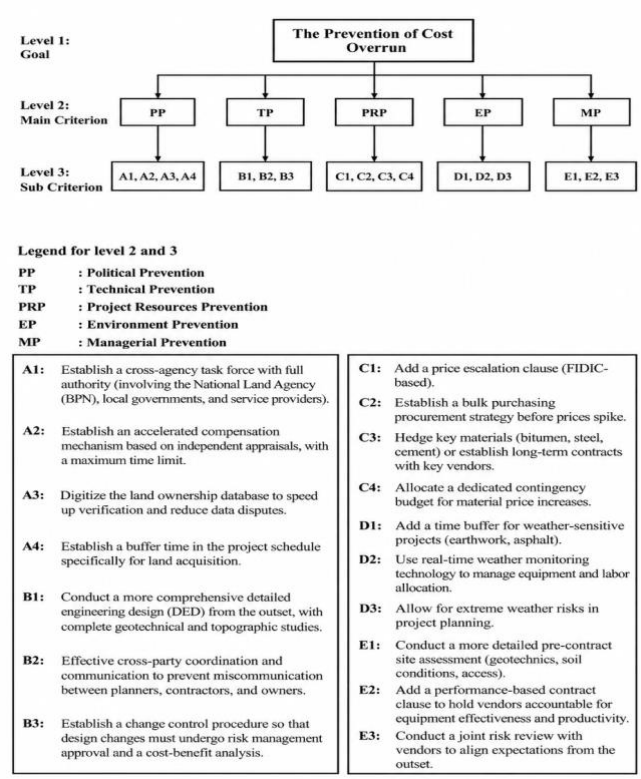


Figure 4. The Structure a Hierarchy of AHP Model

The AHP results show that land acquisition prevention received the highest criterion weight (0.468), followed by design-change prevention (0.250), vendor and contractual issues (0.138), material-price increase prevention (0.092), and natural-condition prevention (0.052). At the alternative level, establishing a cross-agency task force achieved the highest global priority (0.279), followed by comprehensive Detailed Engineering Design (0.168) and detailed pre-contract site assessment (0.091).

These rankings indicate that institutional coordination and front-end preparation were prioritised above more reactive cost-control measures. The pattern is also consistent with wider Indonesian toll-road research showing that contract changes and project-governance risks are important sources of cost escalation. Consistent with the distinction set out in Section 3.3, these rankings describe the AHP-derived priority of prevention categories and mitigation alternatives, not an independently estimated probability or severity ranking of the underlying risks themselves.

4.4 Event Tree Analysis

ETA was subsequently used to evaluate potential consequence pathways associated with the highest-priority risks and the effectiveness of corresponding control measures. Consistent with the semi-quantitative design set out in Section 3.4, the branch values shown in the following event-tree figures (labelled "Probability" for consistency with the original diagram notation) represent the relative, AHP-informed emphasis placed on each pivotal control, and the terminal "Consequence" labels (Rendah/Sedang/Tinggi) denote qualitative severity categories rather than calibrated probabilities of control success, failure, or cost overrun.

For land acquisition delay, incomplete land availability was defined as the initiating event. Stakeholder coordination and accelerated land-acquisition programmes were treated as the principal controls.

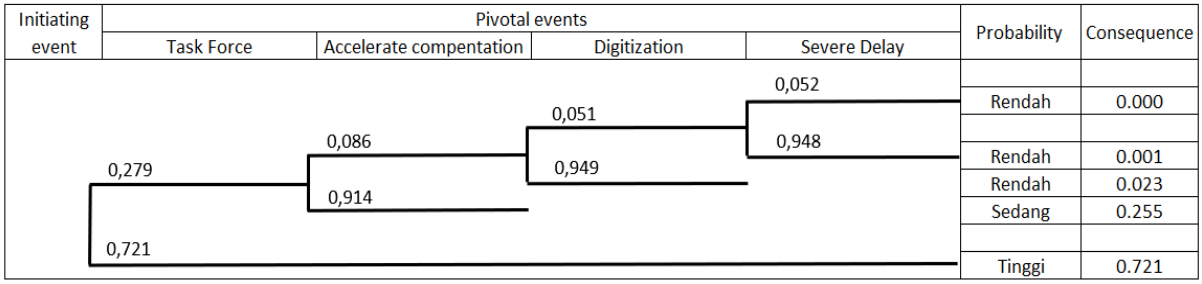


Figure 5. ETA – Delay in Land Acquisition

The analysis showed that successful implementation of both controls resulted in comparatively limited schedule and cost consequences, whereas failure of both controls generated the most severe cost-overrun pathway.

For design changes, modifications during project implementation constituted the initiating event, while technical review and engineering verification served as the principal control mechanisms.

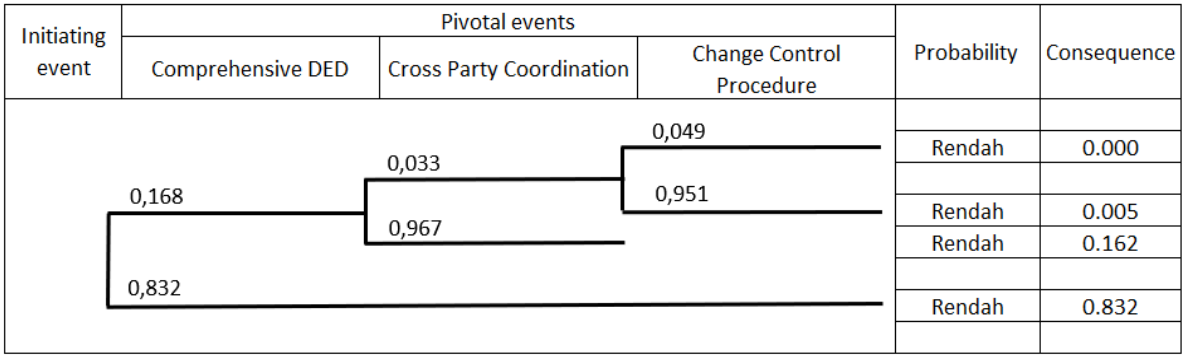


Figure 6. ETA – Design Changes

Effective technical review reduced exposure to rework and additional construction expenditure, whereas inadequate review increased the likelihood of more severe financial consequences.

The ETA framework was also applied to risks associated with vendor and contractual performance.

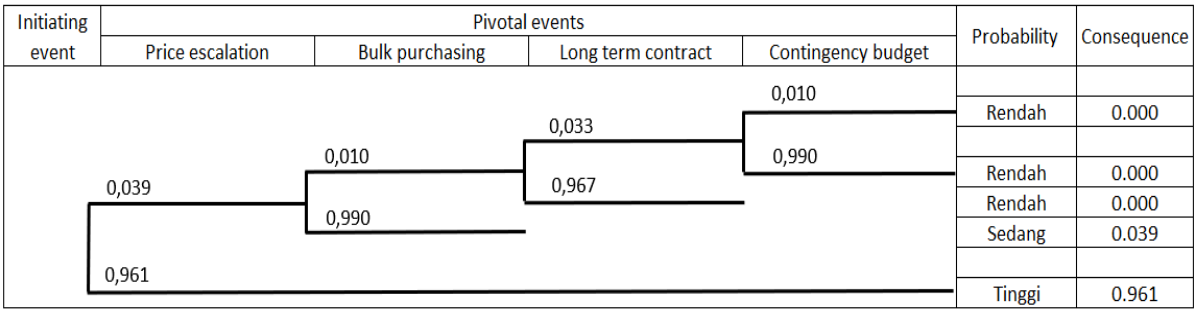


Figure 7. ETA – Vendor & Contract Issues

The analysis demonstrates that procurement planning, contractual controls, and supplier-related mitigation measures can influence the severity of cost consequences. Overall, ETA confirms that the effectiveness of preventive and corrective controls plays an important role in determining whether initiating risk events develop into severe cost overruns.

Taken together, the RCA, AHP, and ETA results provide a sequential account of cost-overrun risk. RCA identifies the underlying causes, AHP determines the relative priority of mitigation strategies, and ETA demonstrates how the success or failure of controls can alter consequence pathways. The results therefore highlight land acquisition governance, front-end engineering preparation, and contractual or vendor risk control as central intervention areas for the Serbelawan–Pematang Siantar project. Because branch values are relative and AHP-informed rather than independently estimated probabilities, these results should be read as indicating the relative ordering of consequence severity across pathways and control scenarios, rather than as point estimates of the probability of a severe cost overrun.

5. DISCUSSION

The findings indicate that cost overruns in the Serbelawan–Pematang Siantar Toll Road are produced by interconnected institutional, technical, contractual, and market-related risks rather than by isolated construction failures. Land-acquisition prevention received the highest AHP weight, followed by design-change prevention, vendor and contractual issues, material-price escalation, and natural conditions. This pattern is consistent with evidence that highway cost and schedule performance are shaped by land acquisition, design and scope changes, contractor weaknesses, financial constraints, procurement problems, and regulatory uncertainty (Atapattu et al., 2023; Mahmud et al., 2021; Sharma et al., 2021; Zhasmukhambetova et al., 2025). The Indonesian toll-road literature reaches a similar conclusion, particularly regarding contract changes, land readiness, contractor performance, and procurement risk (Sandhyavitri et al., 2017; Wibowo & Santoso, 2024; Yosritzal et al., 2019). Importantly, the results suggest different transmission mechanisms. Land acquisition primarily generates a delay-mediated pathway through restricted work-front access, disrupted sequencing, prolonged overhead, financing pressure, and productivity losses, whereas design and scope changes generate a more direct budget-growth pathway through additional quantities, redesign, rework, and change orders (Sihombing, 2017; Sihombing et al., 2018; Wibowo & Santoso, 2024). This distinction is reinforced by Sasmito and Amin (2026), who identify poor planning, technical design changes, discrepancies between plans and site conditions, land-acquisition delays, and inadequate stakeholder coordination as major change-order drivers in Indonesian toll-road projects. Wibowo and Santoso (2024) similarly show that projects experiencing original-contract changes had materially higher average cost overruns than the full sample.

The prioritisation of a cross-agency task force, comprehensive Detailed Engineering Design, and detailed pre-contract site assessment further demonstrates that effective cost-overrun management begins with front-end governance and project readiness, not merely corrective cost control during construction. This interpretation is consistent with research emphasising the importance of project preparation, monitoring, audit, incentive alignment, procurement quality, and contractual governance in Indonesian toll-road performance (Mohamed et al., 2019; Winata & Gultom, 2024; Wirahadikusumah et al., 2018). Winata and Gultom (2024), in particular, show that PPP contract-model selection shapes governance arrangements and construction performance, indicating that cost outcomes are partly determined by institutional design before construction begins. The broader evidence also supports design maturity, land-readiness gating, strict change-order control, stronger contractor selection, integrated schedule-cost-procurement monitoring, and clearer risk allocation as key mitigation mechanisms (Isvara et al., 2023; Pratama et al., 2023; Rani et al., 2025; Wibowo & Alfen, 2015). The ETA findings deepen this interpretation by showing that initiating risks do not inevitably produce severe overruns; consequences depend on whether governance and control mechanisms function effectively. Successful stakeholder coordination and land-

acquisition acceleration reduce the consequences of incomplete land availability, while effective technical review and engineering verification constrain the financial impact of design changes. Thus, the integrated RCA–AHP–ETA framework contributes by linking why risks arise, which risks deserve priority, and how control effectiveness alters their consequences, rather than reducing risk management to a static ranking exercise.

These findings also extend the discussion from construction management to maritime hinterland infrastructure. Because the Serbelawan–Pematang Siantar section forms part of a wider corridor connected to Kuala Tanjung, its timely and financially sustainable delivery can be interpreted as an enabling condition for reliable port–hinterland connectivity. This study does not directly measure port throughput, freight costs, or shipping performance, so the contribution lies not in claiming a direct maritime-logistics effect, but in demonstrating how project-level governance, design, procurement, and land risks can affect the delivery reliability of infrastructure serving a broader maritime corridor. This interpretation is consistent with Li et al. (2023), who find that improved maritime connectivity has a durable positive effect on regional economic growth and identify transport infrastructure expansion as one channel through which such benefits are realised. Conceptually, the findings support three interconnected cost-transmission pathways: direct budget-growth risks arising from design and procurement changes, cost-of-delay risks generated by land and coordination failures, and governance/financing transmission risks associated with contract structure, payment processes, and institutional readiness. For maritime hinterland projects, this means cost reliability should be understood as part of infrastructure-system reliability: stronger front-end preparation, inter-agency coordination, design control, procurement integration, and contractual risk allocation can reduce the likelihood that project-level failures delay the wider economic connectivity that the corridor is intended to support.

Because the evidence base is a single toll-road project assessed by four subject matter experts, the identified priorities should be read as lessons from this particular case rather than as generalisable priorities for maritime infrastructure in emerging economies as a whole. Land acquisition was clearly the highest-priority risk-prevention category in this case, but other projects may face different dominant risks, such as financing constraints, environmental approvals, procurement problems, or contractor capacity; the relative importance of prevention categories identified here should therefore be treated as transferable lessons that may inform, rather than directly predict, priorities in other maritime hinterland infrastructure settings.

Mitigation Responsibilities and Implementation Stages

6. CONCLUSION

This study demonstrates that cost overruns in the Serbelawan–Pematang Siantar Toll Road are driven by interconnected institutional, technical, contractual, and market-related risks rather than by isolated construction problems. Land-acquisition prevention emerged as the highest-priority risk category, followed by design-change prevention,

vendor and contractual issues, material-price escalation, and natural conditions. The most important mitigation priorities were cross-agency coordination, comprehensive Detailed Engineering Design, and detailed pre-contract site assessment. These findings indicate that effective cost-overrun management should begin at the front end of project development through stronger land readiness, design maturity, stakeholder coordination, procurement planning, and contractual risk control.

The study contributes by positioning toll-road cost-overrun management within the broader context of maritime hinterland infrastructure and by integrating RCA, AHP, and ETA into a sequential framework linking root causes, mitigation priorities, and consequence pathways. From a managerial and policy perspective, the results emphasise that cost reliability depends on the effectiveness of governance and preventive controls before and during project implementation. For infrastructure connected to maritime corridors, stronger project readiness and risk governance can support the timely and financially sustainable provision of land-based infrastructure serving wider port–hinterland connectivity.

The findings should nevertheless be interpreted within the limitations of a single-project case study and a relatively small expert panel. In addition, the study does not directly measure downstream maritime outcomes such as port throughput, freight costs, or logistics performance. Future research should therefore apply the RCA–AHP–ETA framework across multiple toll-road and port–hinterland projects, involve more diverse expert groups, and compare different contractual and governance arrangements. Further studies may also integrate Monte Carlo simulation, DEMATEL, Bayesian networks, or system-dynamics approaches and explicitly examine how infrastructure cost and schedule reliability influence measurable maritime-logistics and regional-economic outcomes.

Author Contributions

S. R. B.: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Validation, Resources, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing.
T. F.: Conceptualization, Supervision.

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