

Original Research Article

Risk Management Analysis in Delays of Sigli – Banda Aceh Toll Road Construction: A Focus on Section-1 Padang Tiji - Seulimum

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Highlights:

- Risk factors contributing to delays in the construction of the Sigli-Banda Aceh Toll Road, focusing on Section-1 (Padang Tiji-Seulimum).
- The research identifies operational, material, contractual, design, and environmental risks, with key issues stemming from land acquisition delays, material shortages, and adverse weather conditions.
- There is a need for effective risk management practices to mitigate potential delays and financial losses.

Abstract: The construction of the Sigli–Banda Aceh Toll Road, particularly Section-1 (Padang Tiji–Seulimum), as part of Indonesia’s National Strategic Projects, is crucial for improving regional connectivity and economic development. However, delays in its implementation pose significant challenges. This research was conducted to analyze the key risk factors contributing to project delays, formulate the core problems, and propose mitigation strategies that can benefit stakeholders involved in similar large-scale infrastructure developments. The study aims to identify the types of risks affecting the project timeline and assess their impact and likelihood. A combination of qualitative and quantitative methods was used. Data were collected through field observations, document reviews, and interviews with project stakeholders, including contractors, consultants, and government representatives. The analysis involved the use of the Probability Impact Matrix to evaluate risk severity and Fault Tree Analysis to trace root causes of delays. Results show that the most significant risk factors include delays in land acquisition, shortage of construction materials, and adverse weather conditions. Contractual ambiguities and design-related changes also contribute to schedule disruptions. The research highlights the importance of early risk identification, continuous monitoring, and adaptive risk management strategies. These findings offer practical recommendations to enhance project planning and execution in future infrastructure initiatives.

Keywords: Risk management, construction delays, toll road project, probability impact matrix, fault tree analysis

1. Introduction

Infrastructure development is crucial for economic growth and regional connectivity. Toll roads, as integral components of transportation networks, facilitate efficient movement of goods and people, thereby enhancing economic activities and societal welfare [1]. However, large-scale construction projects often encounter significant challenges, including financial constraints, technical complexities, and unforeseen risks. Recent studies highlight that such projects are particularly susceptible to cost overruns and schedule delays due to inherent uncertainties and inadequate risk management practices [1, 2].

The Sigli-Banda Aceh Toll Road project, a key segment of Indonesia's Trans-Sumatera Toll Road initiative, exemplifies these challenges. Spanning 74.2 kilometers, the project aims to enhance connectivity between Banda Aceh and Medan, promoting economic integration and mobility. Despite its strategic importance, the project has faced substantial delays, particularly in Section-1 (Padang Tiji-Seulimum), primarily due to land acquisition issues. Reports indicate that only 12.7% of land acquisition and 0.13% of physical construction had been completed as of recent assessments [3].

Delays in infrastructure projects are a global concern, often resulting from a combination of technical, managerial, and external factors. Common issues include poor stakeholder coordination,

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material shortages, adverse weather conditions, and legal disputes over land acquisition [1, 4]. These factors not only disrupt project timelines but also inflate costs and strain relationships among stakeholders [5]. For instance, a study on construction projects in the United States found that cost overruns often lead to significant delays and disruptions, prolonging project timelines and escalating indirect costs such as labor and operational expenses [6].

Effective risk management is widely recognized as essential in addressing these challenges. It involves systematic identification, analysis, and mitigation of potential threats to project objectives [7]. Tools such as the Probability Impact Matrix (PIM) and Fault Tree Analysis (FTA) provide structured approaches for evaluating risks and prioritizing mitigation efforts [8, 9]. For example, a study demonstrated the effectiveness of PIM in quantifying and ranking risks in large-scale projects, enabling decision-makers to focus on high-priority issues [10]. Similarly, FTA has been highlighted as valuable in identifying root causes of project delays and designing targeted interventions [11].

In addressing construction delays, recent research emphasizes the importance of adaptive project management strategies and stakeholder collaboration. Proactive engagement with landowners, government agencies, and contractors is crucial to aligning project objectives and reducing procedural [12]. Furthermore, the integration of digital tools such as Building Information Modeling (BIM) and real-time data monitoring systems has shown promise in mitigating risks associated with design changes and resource allocation [13]. These technologies enhance transparency and streamline decision-making processes, which are particularly critical in large-scale projects with multiple stakeholders. For instance, BIM has been successfully implemented in several infrastructure projects across Southeast Asia, demonstrating significant improvements in efficiency and risk reduction [14]. These advancements underscore the need for incorporating innovative approaches into risk management frameworks to address the complexities of modern construction projects.

This study aims to explore the risk factors contributing to delays in the Sigli-Banda Aceh Toll Road project, with a specific focus on Section-1. Despite its strategic importance, challenges such as delays in land acquisition, material shortages, and adverse weather conditions have significantly hindered progress. This raises critical questions: What are the key risk factors causing delays in the construction of Section-1? How do these risks impact the timeline and overall project objectives? By addressing these questions, the study seeks to provide actionable recommendations for mitigating delays and ensuring project success. Insights from this research are expected to benefit not only the Sigli-Banda Aceh project but also similar infrastructure initiatives worldwide, contributing to the broader discourse on risk management in construction projects.

2. Literature Review

The successful execution of large-scale infrastructure projects, such as toll roads, is pivotal for economic development and regional integration. However, these projects frequently encounter significant challenges, including delays and cost overruns, which can undermine their intended benefits. Understanding the underlying causes of these delays and implementing effective risk management strategies are essential for improving project outcomes.

2.1. Cause of Construction Delays

Construction delays are a persistent issue worldwide, with underlying causes varying across regions and project types. Recent studies provide valuable insights into these delays. For instance, analyzed infrastructure projects in Malaysia and identified land acquisition delays, contractor-related inefficiencies, and financing issues as key contributors [15]. They concluded that early stakeholder engagement and transparent financing mechanisms are crucial for mitigating such risks [16].

In India, [1] investigated large-scale public projects and highlighted inadequate project planning and communication gaps between stakeholders as critical factors. Their findings emphasized the importance of robust pre-construction risk assessments to prevent project timeline disruptions. Similarly, [17] studied delays in urban infrastructure projects in the Gulf region, where delays were often attributed to weather conditions, regulatory changes, and resource shortages.

In Indonesia, studies have also shed light on specific challenges [3], evaluated the Trans-Sumatera Toll Road project, noting that political and bureaucratic hurdles, along with insufficient land acquisition processes, significantly impacted project progress. Their research underscored the importance of government support and streamlined procurement systems.

2.2. Risk Management in Construction Projects

The critical role of risk management in mitigating delays and inefficiencies in construction projects has been extensively explored in recent studies. Risk management involves identifying, analyzing, and addressing potential risks that could impact project timelines, budgets, or quality. [2] emphasizes that risk management not only mitigates potential issues but also improves decision-making by providing a structured approach to evaluate and prioritize risks.

A study by [18] highlights the importance of integrating risk management into the early stages of project planning. Their research on Australian infrastructure projects revealed that early risk identification and mitigation significantly reduced cost overruns and delays. They advocate for the adoption of iterative risk assessment processes that adapt to changing project conditions, ensuring proactive responses to unforeseen challenges.

The use of digital tools in risk management has gained considerable attention in recent years. [19] explored the application of artificial intelligence (AI) in construction risk management, particularly in predicting and addressing resource shortages and schedule deviations. Their findings demonstrated that AI-based models provided accurate forecasts, enabling project managers to reallocate resources dynamically and mitigate potential delays.

Building Information Modeling (BIM) has also emerged as a powerful tool for enhancing risk management in construction projects [20]. [21] investigated BIM applications in large-scale infrastructure projects in Southeast Asia, finding that BIM improved coordination among stakeholders and reduced risks related to design errors and material procurement. They concluded that incorporating BIM into risk management frameworks enhances both efficiency and project outcomes.

Furthermore, collaborative approaches to risk management have shown significant potential. [12] studied public-private partnership (PPP) toll road projects in Vietnam and highlighted that collaborative risk-sharing mechanisms among stakeholders led to better risk distribution and mitigation. Their findings underscore the value of shared responsibility in addressing project risks effectively.

Another perspective on risk management involves real-time data integration. [13] proposed a model combining Internet of Things (IoT) technologies with predictive analytics to monitor and address risks in real-time. Applied in Middle Eastern toll road projects, this approach enhanced transparency and enabled quick responses to emerging risks, such as environmental hazards and logistical bottlenecks.

In the context of large-scale projects, structured methodologies remain indispensable. [8] confirmed the utility of the PIM in prioritizing risks based on their likelihood and impact, while [9] demonstrated the effectiveness of FTA in identifying root causes of critical risks. Both studies highlight the importance of adopting a combination of quantitative and qualitative tools to comprehensively manage risks.

Collectively, these studies underline the significance of risk management in ensuring project success. They also point to the evolving nature of risk management practices, driven by advancements in technology and the growing need for collaboration among stakeholders. As infrastructure projects become more complex, integrating innovative tools and adaptive strategies into risk management frameworks will be crucial for addressing the multifaceted challenges they present.

2.3. Related Research and Applications

The application of risk management strategies in construction projects has been increasingly explored in recent years, with a focus on improving efficiency, reducing delays, and ensuring cost-effectiveness. Many studies emphasize the practical benefits of integrating advanced tools and methodologies into infrastructure projects.

One area of significant development is the use of Building Information Modeling (BIM) for risk management. BIM has been shown to effectively reduce rework and minimize delays by improving communication among design and construction teams [22]. Similarly, BIM applications in toll road projects have been found to enhance stakeholder coordination, particularly during the planning and execution phases, by providing real-time access to project data [14]

The adoption of digital technologies has also been a key focus in addressing construction risks. IoT devices integrated with risk management platforms provide real-time monitoring of environmental conditions and equipment performance, allowing project managers to preemptively address risks such as extreme weather and equipment failure [13].

Additionally, the application of artificial intelligence (AI) in predictive risk management has shown promising results. Machine learning algorithms applied to historical data from large-scale

projects enable the identification of potential delays and cost overruns, enhancing proactive decision-making in resource allocation and schedule optimization [19].

Collaborative risk management approaches have proven particularly effective in PPP projects. Collaborative risk-sharing frameworks between public entities and private contractors significantly improve project outcomes by addressing financial, operational, and environmental risks more resiliently [12]. Similarly, early stakeholder engagement and transparent communication channels mitigate risks associated with land acquisition and regulatory compliance, as observed in the Indonesian Trans-Sumatera Toll Road project [3].

The role of real-time data integration has also been highlighted in recent studies. A dynamic risk management system using big data analytics allows project teams to monitor risk indicators continuously, providing actionable insights to prevent delays and cost escalations [23]. Integrating big data analytics into risk management frameworks could revolutionize how risks are managed in complex infrastructure projects.

In addressing environmental risks, adaptive strategies that incorporate environmental assessments into the early stages of project planning, coupled with ongoing monitoring using satellite data and IoT sensors, have proven effective [4]. This approach is particularly valuable in mitigating risks related to flooding and extreme weather, which are common issues in tropical regions.

2.4. Theoretical Framework of Risk Management

Risk management in construction projects is a systematic process of identifying, analyzing, and mitigating potential risks that may affect project objectives. Theoretical foundations of risk management emphasize its role in reducing uncertainties and enhancing decision-making during project execution [2, 24]. Risk management frameworks generally involve iterative steps, including risk identification, risk assessment, response planning, and continuous monitoring. These steps help project teams to anticipate potential disruptions and allocate resources efficiently to address high-priority risks.

The distinction between probabilistic and deterministic approaches is central to risk management theory. Probabilistic approaches assess risks using statistical methods to predict the likelihood and impact of potential issues, allowing for more dynamic decision-making [7]. Conversely, deterministic models focus on predefined risk scenarios and fixed outcomes, making them suitable for projects with stable environments and minimal uncertainties. The choice between these methods depends on the complexity and scope of the project.

In large-scale infrastructure projects like toll roads, adopting a tailored risk management framework is crucial. For example, integration of proactive and reactive risk management approaches has been found effective in addressing both anticipated and emerging risks [18]. Theoretical advancements in combining traditional frameworks with digital tools, such as real-time risk tracking systems, further emphasize the evolution of risk management in modern construction practices.

2.5. Type of risk in construction projects

Construction projects face a wide range of risks that can disrupt timelines, inflate costs, and compromise quality. Operational risks, such as delays in resource allocation or workforce inefficiencies, are among the most common in large-scale projects. These risks often arise due to inadequate planning or unforeseen site conditions, as highlighted in studies by [1]. Poor communication and coordination among stakeholders further exacerbate operational challenges, leading to significant delays and cost overruns.

Financial risks, including budget overruns and funding delays, are another critical concern. Fluctuations in material costs and unforeseen expenditures can strain project budgets, especially in regions with volatile economic conditions [25]. In toll road projects, financing mechanisms, such as PPP, can introduce additional complexities, requiring robust financial planning to ensure project viability.

Environmental risks are increasingly relevant, particularly in regions prone to natural disasters or extreme weather conditions. Flooding, landslides, and other environmental factors can disrupt construction activities, as observed in Southeast Asia's infrastructure projects [4]. Additionally, regulatory and social risks, such as land acquisition disputes and community opposition, often delay project execution. These risks highlight the importance of comprehensive risk assessments that account for both internal and external project environments.

3. Methodology

This study adopts a mixed-methods approach, combining both qualitative and quantitative research techniques to identify, analyze, and evaluate the risk factors contributing to delays in the Sigli–Banda Aceh Toll Road construction, with a specific focus on Section-1 (Padang Tiji–Seulimum). The methodological framework is structured to ensure a comprehensive understanding of the risks and their potential impacts on project timelines. A visual representation of the methodology process is presented in Figure 1. The diagram outlines the flow from the research design stage to data collection, analysis, validation, and the final findings. It highlights how qualitative and quantitative methods integrate to produce actionable results.

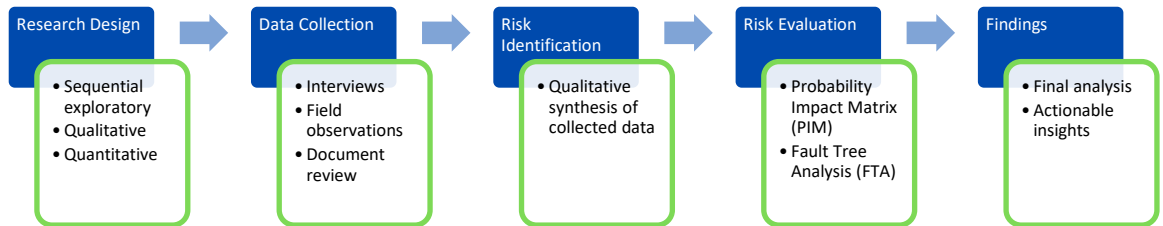


Figure 1. Methodology Process Diagram

3.1. Research Design

The study follows a sequential exploratory design, which begins with qualitative data collection and analysis to identify risk factors, followed by quantitative techniques to prioritize and validate these risks. This design is widely recognized for its ability to integrate rich contextual insights with measurable data [26]. The combination of PIM and FTA ensures a comprehensive understanding of both the magnitude and root causes of risks [2].

3.2. Probability Impact Matrix

The PIM was used to prioritize risks based on their probability and impact scores. This method is a standard quantitative tool for risk prioritization in construction projects [27]. The steps involved were as follows:

- Risk Scoring:** Each risk was assigned a score by multiplying its probability rating with its impact rating: $\text{Risk Score} = \text{Probability Rating} \times \text{Impact Rating}$
- Risk Categorization:** Risks were classified into three categories based on their scores:
 - High Risk: Score > 15
 - Medium Risk: Score 8–15
 - Low Risk: Score < 8
- Application:** The prioritized risks were plotted on a matrix, which helped visualize the most critical risks requiring immediate attention.

PIM is particularly effective for toll road projects due to its simplicity and ability to rank risks for practical decision-making [22].

3.3. Fault Tree Analysis

The FTA was used to investigate the root causes of high-priority risks identified through PIM. The FTA process involved:

- Building Fault Trees:** Graphical representations were created to map the logical relationships between risks and their underlying causes.
- Identifying Root Causes:** The diagrams helped trace risk pathways to identify critical triggers and their interdependencies.
- Analysis:** Each fault tree provided insights into systemic failures and suggested targeted mitigation strategies.

FTA has been widely adopted in infrastructure projects to analyze complex, interrelated risks systematically [9]. For example, high-priority risks like delays in land acquisition were linked to bureaucratic inefficiencies and stakeholder misalignments.

4. Results

This section presents the findings from the analysis of risk factors contributing to delays in the Sigli-Banda Aceh Toll Road project, particularly in Section-1 (Padang Tiji-Seulimum). The results are organized to address the research objectives, incorporating both qualitative and quantitative insights obtained through PIM, FTA, and supporting thematic analysis.

4.1. Key Risk Factors Identified

The analysis identified 15 major risk factors across five categories:

1. Operational risks:
 - Insufficient workforce allocation (Risk Score: 18)
 - Delays in material delivery (Risk Score: 16)
2. Financial risks:
 - Delayed project financing from stakeholders (Risk Score: 17)
 - Fluctuating material costs (Risk Score: 14)
3. Contractual risks:
 - Ambiguities in contractual agreements (Risk Score: 15)
 - Disputes among contractors and subcontractors (Risk Score: 14)
4. Environmental risks:
 - Flooding and weather disruptions (Risk Score: 16)
 - Poor soil conditions in construction zones (Risk Score: 15)
5. Design and technical risks:
 - Incomplete or outdated design documents (Risk Score: 16)
 - Challenges in adapting to updated regulatory requirements (Risk Score: 13)

These findings were ranked using the PIM, which categorized risks as high, medium, or low based on their scores.

4.2. High-Priority Risks

The Probability Impact Matrix revealed that the most critical risks, scoring above 15, were primarily operational and financial:

- Land acquisition delays: Identified as the highest risk, driven by bureaucratic inefficiencies and community disputes.
- Material shortages: Caused by supply chain disruptions and limited supplier capacity.

4.3. FTA-Based Findings

FTA is a powerful tool used to systematically identify and analyze the root causes of critical risks in construction projects. In this study, FTA findings for high-priority risks, such as "Land Acquisition Delays" and "Material Shortages", play a pivotal role in informing decision-making and developing targeted mitigation strategies.

Using FTA, root causes for the high-priority risks were identified:

- Land acquisition delays: Traced to protracted negotiations with local communities, lack of alignment between stakeholders, and slow approval processes by regulatory authorities.
- Material shortages: Linked to global supply chain constraints, insufficient inventory management, and unpredictable cost fluctuations.

The FTA diagrams provided a systematic breakdown of these risks, showing interdependencies and cascading effects on project timelines. The findings provide a foundation for understanding complex, systemic risks in construction projects. They ensure that mitigation strategies are not only reactive but also preventive and tailored to the unique challenges of the project. In this study, FTA findings are instrumental in aligning resources, improving stakeholder collaboration, and reducing delays in the Sigli-Banda Aceh Toll Road project.

4.4. Thematic Insights from Qualitative Data

Thematic analysis of interview data highlighted additional contextual insights:

- Stakeholder Coordination: Fragmented communication among government agencies and contractors exacerbated delays.
- Community Relations: Lack of transparent engagement with local communities led to resistance during the land acquisition process.

- Environmental Challenges: Unpredictable flooding due to inadequate pre-construction environmental assessments.

4.5. Impact on Project Timelines and Costs

The combined impact of these risks resulted in significant delays:

- Project progress was reported at only 12.7% completion for land acquisition and 0.13% for physical construction, despite initial targets of 50% completion by the current timeline.
- Cost overruns were projected to exceed the allocated budget by approximately 15%, primarily due to material cost increases and extended project duration.

4.6. Effectiveness of Risk Management Strategies

Current risk management practices were assessed based on stakeholder responses:

- Strengths: Clear documentation of identified risks and regular project status reporting.
- Weaknesses: Limited implementation of proactive mitigation measures, such as real-time monitoring tools or contingency planning.

These results provide actionable insights to inform the recommendations in the subsequent section.

An overview of the average risk scores across categories is presented in Figure 2, showing that Operational and Financial risks received the highest scores. These categories pose the most significant threats to project performance and should be prioritized in risk mitigation planning. A more detailed breakdown of each risk factor is provided in Table 1, which includes the probability, impact, calculated risk score, and priority level. For instance, risks such as workforce allocation issues and delayed project financing have been classified as high priority due to their significant impact.

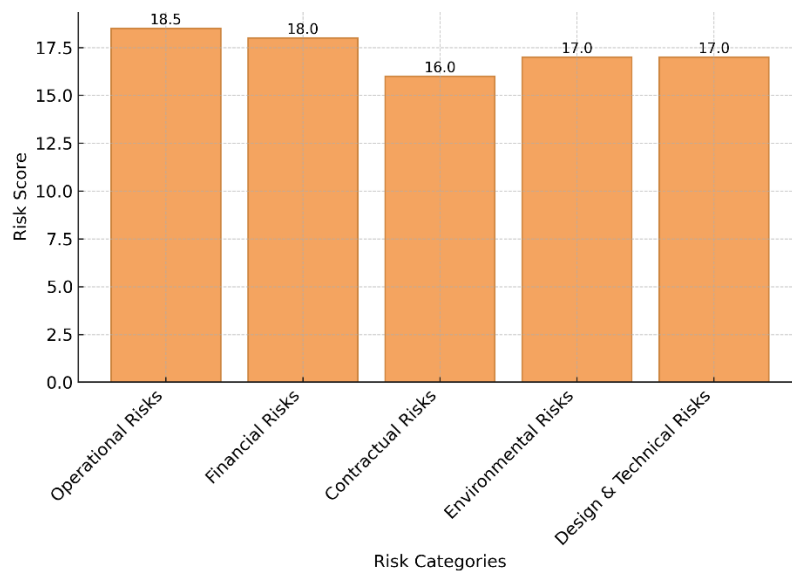


Figure 2. Risk Scores by Categories

Table 1. Risk Scores for Each Categories

Risk category	Risk factor	Probability	Impact	Risk score	Priority level
Operational	Workforce Allocation Issues	4	4	16	High
Financial	Delayed Project Financing	4	4	17	High
Contractual	Ambiguities in Agreements	3	5	15	Medium
Environmental	Flooding Disruptions	4	4	16	High
Design & Technical	Outdated Design Documents	3	4	12	Medium

To analyze the underlying causes of one of the major risks—land acquisition delays—a FTA was conducted. As shown in Figure 3, the FTA diagram traces the top event through a series of contributing factors such as community resistance, stakeholder misalignment, and delays in regulatory approvals, further decomposed into root causes like poor communication, unclear policies, and prolonged negotiations.

Risk prioritization was also visualized using the PIM, presented in Figure 4. This matrix highlights the severity of risks by mapping the combination of probability and impact using a color gradient. It serves as a strategic decision-making tool to identify which risks demand immediate mitigation.

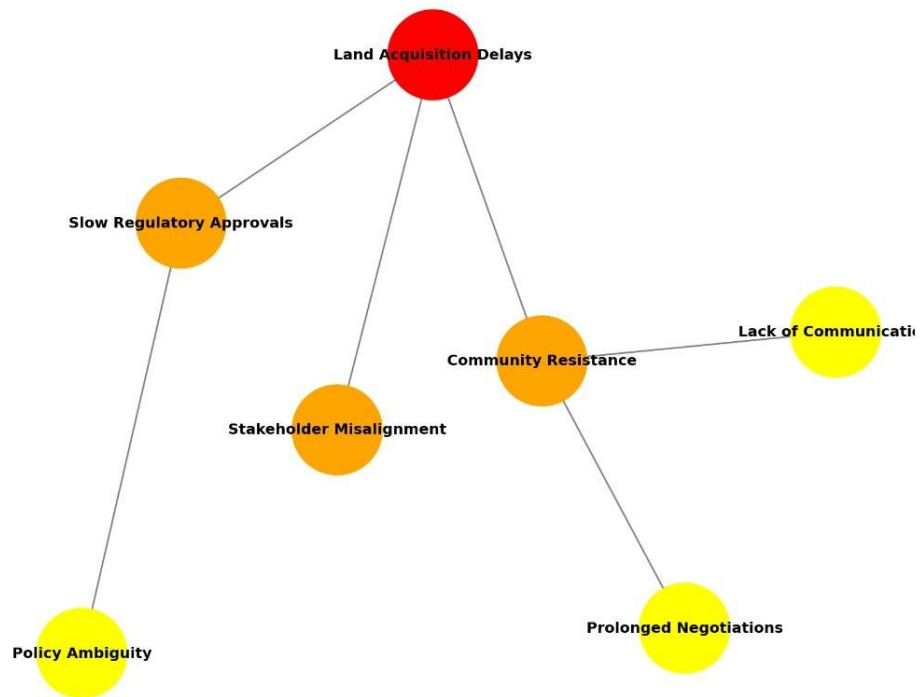


Figure 3. FTA for Land Acquisition Delays

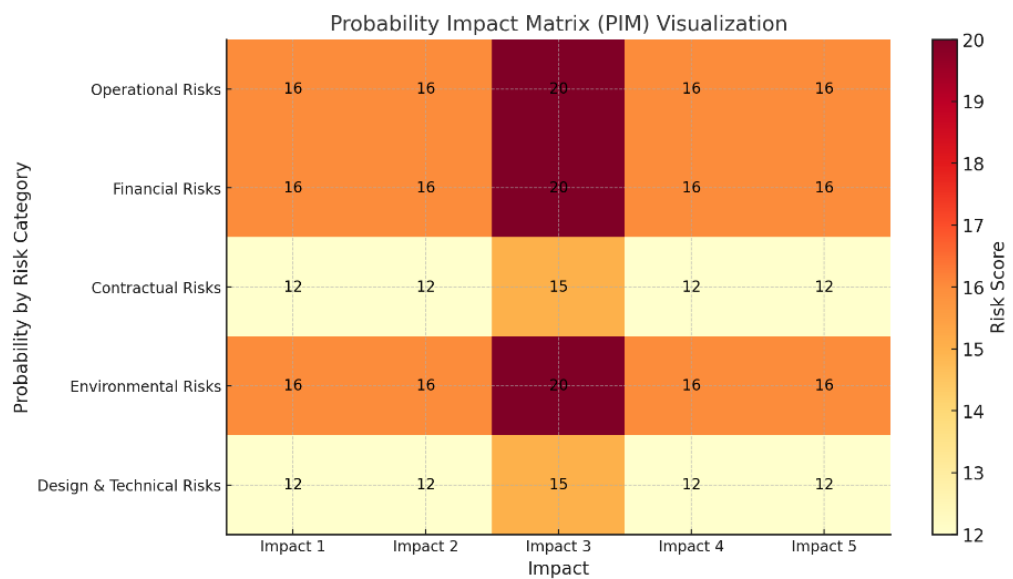


Figure 4. FTA for Land Acquisition Delays

5. Discussion

The findings from the PIM revealed that operational risks (such as workforce allocation issues) and financial risks (such as delayed project financing) are the most critical categories impacting project timelines. These align with studies by [1, 12], which similarly identified operational inefficiencies and funding delays as significant contributors to construction delays. The prominence of land acquisition delays in this study underscores a persistent challenge in infrastructure projects, particularly in developing countries like Indonesia. The root causes identified through FTA—such as community resistance and regulatory inefficiencies—reflect findings by [3], who emphasized the need for stakeholder alignment and transparent communication in mitigating such risks. The findings also suggest that tools like PIM and FTA can be further enhanced by integrating them into digital platforms, allowing for automated risk assessments and predictive analytics. This recommendation aligns with emerging trends in construction risk management, as highlighted by [13].

One of the key themes emerging from the qualitative analysis is the lack of alignment among stakeholders, including contractors, regulatory bodies, and local communities. This fragmentation exacerbates delays in critical activities such as land acquisition and material procurement. Similar issues were noted previously [12], where in their study on PPP projects, which emphasized the importance of collaborative risk-sharing mechanisms. The findings suggest that improving stakeholder engagement through structured communication strategies and early consultations could mitigate many of these challenges. For instance, involving local communities in the planning process could reduce resistance during land acquisition, as also recommended by a previous study [4].

The study identified environmental risks, such as flooding and poor soil conditions, as significant contributors to delays. These findings are consistent with research by [4], which emphasized the need for integrating environmental risk assessments into project planning. For the Sigli-Banda Aceh Toll Road project, proactive measures such as detailed geotechnical surveys and climate-resilient designs could address these risks effectively.

The results of this study offer several practical lessons for managing risks in large-scale infrastructure projects: Streamlining regulatory processes, simplifying bureaucratic procedures could reduce delays in land acquisition and approval processes. This aligns with recommendations by [21]. Adopting collaborative models, developing collaborative frameworks for stakeholder engagement, similar to those used in PPP projects, could enhance coordination and align priorities. Enhancing risk monitoring capabilities, incorporating real-time monitoring tools, such as IoT sensors and big data analytics, could enable dynamic risk tracking and timely interventions.

This study contributes to filling research gaps by providing context-specific insights into risk management in Indonesian infrastructure projects. Unlike many studies that focus on isolated risks, this research integrates PIM and FTA to provide a comprehensive analysis of both high-priority risks and their root causes. Additionally, the findings highlight the need for future research to explore the integration of digital tools into risk management frameworks, particularly in resource-constrained settings. Longitudinal studies tracking the effectiveness of these tools over the project lifecycle could further enhance the understanding of risk dynamics. Effective risk management in large-scale construction projects requires a combination of advanced tools, collaborative frameworks, and proactive strategies. This present study does not only inform the ongoing management of the Sigli-Banda Aceh Toll Road project but also provide valuable insights for similar infrastructure initiatives globally.

6. Conclusion

This study examined the risk factors contributing to delays in the Sigli–Banda Aceh Toll Road project, particularly in Section-1 (Padang Tiji–Seulimum), through the application of PIM and FTA.

- 1) The analysis identified land acquisition delays, labor shortages, and material supply disruptions as the most critical risks, primarily driven by bureaucratic inefficiencies and poor stakeholder coordination.
- 2) The use of PIM and FTA effectively supported the identification, prioritization, and root cause analysis of these risks. In line with the research objectives, the study emphasizes the importance of early stakeholder engagement, collaborative risk-sharing mechanisms, and the strategic use of digital tools to reduce project delays.
- 3) The findings offer practical insights for improving risk management in large-scale infrastructure projects. Future research is recommended to include additional project sections and explore the long-term role of technology in risk mitigation.

Author Contributions:

Yasir Alhammadi contributed in conceptualization, methodology, software, formal analysis, investigation, resources, data curation, writing—original draft, writing—review and editing, supervision, and funding acquisition. Mazem M. Omer contributed in investigation, and writing—review and editing. Muhammad Azmi contributed in software, visualization, and project administration. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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