

RISK ANALYSIS OF THE AMANAH CENTER BUILDING CONSTRUCTION PROJECT USING THE BOWTIE METHOD

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Abstract

Building construction projects face uncertainties that may affect time, cost, and quality goals. This study aims to identify, categorize, and analyze the dominant risks in the Amanah Center Building Project in Ladong Village, Aceh Besar, using the Bowtie method. The Amanah Center is a large-scale project with a total area of 14,646 m², which is susceptible to various risks. The risk factors analyzed include labor risks, contractual risks, design and technology risks, execution risks, material and equipment risks, and force majeure risks. Data were collected through interviews and surveys with project stakeholders, and risks were assessed using a probability-impact matrix on a 1-5 Likert scale. The results show that design changes represent the highest risk factor, with a mean value of 3.19, indicating frequent occurrence. The probability impact matrix further reveals that design and technology risks, particularly design changes, pose a moderate-risk level (score 9.19), which in practice may cause delays of up to two weeks and cost increases of around 10% of affected activities. The Bowtie analysis identifies two key top events: (1) design and technology risks, leading to delays and rework, mitigated through design review and schedule adjustments; and (2) material and equipment risks, associated with poor material quality and price escalation, mitigated through supplier diversification and procurement planning. This study not only provides valuable insights into project risk management but also offers practical recommendations for project managers, emphasizing stricter design review processes and more resilient procurement strategies.

Keywords: Risk analysis; Construction project; Bowtie method; Probability impact matrix

Introduction

The construction industry is a highly complex and dynamic sector, where the execution of construction projects is often associated with a significant degree of uncertainty. This uncertainty stems from various factors such as design changes, resource shortages,

unexpected weather conditions, and technical difficulties, all of which can lead to delays, cost overruns, and compromises in quality (Fernández-Valderrama *et al.*, 2024; Gunduz *et al.*, 2025). Effective risk management plays a crucial role in

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identifying, analyzing, and mitigating these uncertainties to ensure that projects are completed on time, within budget, and to the required quality standards (Aven, 2016; Kumi *et al.*, 2024). Recent studies show that proactive risk management helps in improving the success rate of construction projects by addressing potential risks before they materialize (Kiral, 2025). Moreover, understanding the sources of risk can enhance decision-making processes during project planning and execution (Nguyen and Macchion, 2023).

The construction industry is widely recognized as a complex and dynamic sector in which project execution is subject to a high degree of uncertainty. These uncertainties arise from multiple sources, including design modifications, labor availability, material price volatility, supply chain disruptions, and technical constraints, all of which can adversely affect project time, cost, and quality performance (Fernández-Valderrama *et al.*, 2024; Gunduz *et al.*, 2025). As a result, construction projects are inherently exposed to diverse risks that require systematic identification and effective management throughout the project lifecycle.

One effective tool in construction risk analysis is the Bowtie Method, which visualizes the pathways of risk from potential causes to consequences, and provides insights into possible preventive measures and mitigations. The Bowtie method's ability to map both the causes and effects of risks makes it an invaluable tool in managing complex projects, particularly in large-scale construction projects like the Amanah Center. Studies have highlighted that Bowtie analysis aids in clearly identifying the key risk factors and understanding the relationships between them, which significantly contributes to more accurate risk assessments (Khakzad *et al.*, 2012; De Ruijter and Guldenmund, 2016). In addition, Bowtie provides a structured framework for implementing preventive and corrective measures, making it particularly valuable in construction risk management (Singh *et al.*, 2024; Montero *et al.*, 2025).

The Amanah Center Building Project, located in Ladong Village, Aceh Besar, is a large-scale construction project with a total area of 14,646 m². Given the project's scale and complexity, it is highly susceptible to various risks that could impact its success. Key risk factors for this project include labor risks, contractual risks, design and technology risks, execution risks, material and equipment risks, and force majeure risks. According to recent studies, construction projects in similar environments often face challenges related to resource allocation, unforeseen technical issues, and supply chain disruptions (Fernández-

Valderrama *et al.*, 2024; Yussif *et al.*, 2025). Therefore, a thorough risk analysis using the Bowtie Method is essential to identify critical risks and determine effective mitigation strategies to ensure the project's timely and successful completion.

The Amanah Center is designed as a multifunctional public facility comprising commercial areas, conference halls, and community service offices, with a total budget of approximately IDR 220 billion (USD 14 million) and a construction duration of 30 months. The main stakeholders include the provincial government as the owner, a joint-venture contractor (national and local firms), and several design and supervision-consultants. This context provides a representative case for analyzing risks in large-scale, multi-stakeholder building projects in Indonesia.

Furthermore, the use of the Bowtie Method in analyzing construction risks provides a systematic approach to decision-making in risk management (Khakzad *et al.*, 2012). It enables stakeholders to visualize the risks and their potential impacts while outlining clear preventive actions and contingencies (Aven, 2016). Research has demonstrated that when Bowtie Analysis is applied, it not only identifies risk events but also facilitates the development of mitigation plans, such as the allocation of additional resources, project schedule adjustments, or changes in the design and technology used (Elizabeth *et al.*, 2025; Montero *et al.*, 2025). For large-scale projects, such as the Amanah Center, early identification of risks can help project managers take proactive steps to minimize delays and additional costs, thereby improving overall project outcomes.

Against this background, prior research using the Bowtie method mainly emphasized the visualization of hazards and generic frameworks for risk assessment (De Ruijter and Guldenmund, 2016; Khakzad *et al.*, 2012). However, these studies did not explicitly address the integration of Bowtie with real-time risk monitoring mechanisms or its application to project-specific contexts in developing regions.

This study contributes by (1) applying the Bowtie framework to a large-scale public facility in Aceh Province, Indonesia, (2) integrating quantitative probability-impact scoring with qualitative insights from stakeholders, and (3) demonstrating how Bowtie analysis can be enhanced with real-time monitoring for risks such as design changes and material disruptions. These aspects distinguish the proposed framework and highlight its relevance for both academic and practical applications in similar large-scale projects.

By examining the Amanah Center Building Project through the lens of the Bowtie Method, this study contributes by (1) applying the Bowtie framework to a large-scale public facility in Aceh Province, Indonesia, (2) integrating quantitative probability-impact scoring with qualitative insights from stakeholders, and (3) demonstrating how Bowtie analysis can be enhanced with real-time monitoring for risks such as design changes and material disruptions. Unlike prior Bowtie-based studies that mainly emphasized generic frameworks, this study highlights project-specific contexts in developing regions. These aspects distinguish the proposed framework and underline its relevance for both academic and practical applications in similar large-scale projects.

Materials and Methods

Risk management is a critical component in the construction industry, aiming to identify, assess, and mitigate potential risks that could adversely affect project outcomes (Rani *et al.*, 2024b). Various methodologies have been developed to manage these risks effectively, with the Bowtie method gaining prominence in recent years (De Ruijter and Guldenmund, 2016). This chapter provides a comprehensive review of the literature on construction risk management, emphasizing recent studies and the application of the Bowtie method.

Construction Risk Management: An Overview

Construction projects are inherently risky due to their complexity, involvement of multiple stakeholders, and susceptibility to external factors such as economic fluctuations and regulatory changes (Szymański, 2017; Nguyen and Macchion, 2023). Key risks in construction include cost overruns, delays, quality defects, and safety hazards, which can significantly impact project performance (Kumar and Narayanan, 2021; Yussif *et al.*, 2025).

A recent study focusing on construction projects in the Dominican Republic identified key factors contributing to cost and time deviations, including inadequate project planning, unforeseen site conditions, and delays in material procurement (Fernández-Valderrama *et al.*, 2024). The study emphasizes the importance of proactive risk identification and management to mitigate these issues.

Risk management frameworks have evolved to address these challenges. The traditional risk matrix approach is widely used to classify risks based on their likelihood and impact; however,

recent studies suggest integrating advanced techniques such as Monte Carlo simulations and fuzzy logic to enhance risk assessment accuracy (Kumi *et al.*, 2024). Additionally, digital tools like Building Information Modeling (BIM) have been employed to improve risk visualization and decision-making (Han *et al.*, 2025). The increasing adoption of machine learning in construction risk management further enables predictive analytics, allowing for more effective early warning systems (Singh *et al.*, 2024).

In global construction projects, cultural and regulatory differences add another layer of complexity to risk management. Research indicates that multinational construction firms must consider variations in legal frameworks, safety standards, and labor laws to develop comprehensive risk mitigation strategies (Rajapakshe, 2025). Effective communication and collaboration among stakeholders have also been identified as key factors in reducing construction risks (Fernandez-Muniz *et al.*, 2018). Moreover, recent advancements in digital twin technology have enabled real-time risk monitoring and scenario analysis, providing new avenues for proactive risk management in the construction sector (Han *et al.*, 2025).

Risk Analysis

According to the Project Management Institute (2025), risk analysis is the process of seeking more specific information or descriptions about identified risks, including quantifying risks in terms of probability, causes, and interrelationships. The impact estimation involves investigating the effects on construction quality, such as time, cost, and quality. A systematically processed risk analysis can help: 1) Identify, assess, or rank risks clearly; 2) Focus attention on major risks; 3) Clarify loss boundaries and control uncertainties; 4) Minimize potential damage in the worst-case scenarios; 5) Clarify the roles involved in risk management (Fraume *et al.*, 2020; Rani *et al.*, 2025).

Risk evaluation in construction projects depends on the probability of the risk occurring and its potential impact (Rani *et al.*, 2022). Probability refers to the chance of a risk occurring, based on statistical analysis. The probability rating ranges from very small to very large (1 to 5), as shown in Table 1.

Impact scale reflects the negative influence on achieving goals, which can harm the company. The assessment is rated on a scale of 1 to 5, as outlined in Table 2.

According to Rani *et al.* (2024a), the measurement scale is used to assess variables in a research problem, and in this study, a Likert scale

is employed. The Likert scale is used to measure attitudes, opinions, and perceptions on specific objects or phenomena with five response options.

Table 1. Probability Measurement Criteria

Measurement	Criteria	Description
Very Small	< 10%	Rarely occurs
Small	10%-40%	Occasionally happens
Medium	40%-60%	Happens under certain conditions
Large	60%-80%	Frequently occurs
Very Large	80%-95%	Always occurs

Table 2. Impact Rating Criteria

Measurement	Criteria	Description
Very Small	0%-2%	Insignificant financial loss
Small	2%-5%	Minor overhead costs
Medium	5%-10%	Significant financial loss
Large	10%-15%	Major failure or asset loss
Very Large	> 15%	Huge financial loss

The Probability Impact Matrix is widely used as a qualitative method for risk assessment, providing descriptive results and supporting further quantitative investigations (Aven, 2016). The two key risk components, severity (probability of occurrence) and occurrence (impact), are assigned values to classify risk priorities.

Based on the resulting probability-impact scores, the overall risk level is classified into high, medium, and low categories, as summarized in Table 3.

Table 3. Risk Level Indicators

Risk Level	Description
> 14	High
8 – 14	Medium Risk
< 8	Low Risk

Table 4. Risk Frequency and Impact Matrix

Risk = F x D		Impact (D)				
		1	2	3	4	5
Frequency (F)		Very Low (VLO)	Low (L)	Medium (M)	High (H)	Very High (VHI)
1	Rare	L	L	L	L	M
2	Unlikely	L	L	M	M	H
3	Occasionally	L	M	M	H	H
4	Often	L	M	H	H	H
5	Always	M	H	H	H	H

The interaction between risk frequency and impact is evaluated using a risk frequency-impact matrix, as presented in Table 4.

From the matrix above, high-risk scenarios are marked in red (high risk), medium risks in yellow (medium risk), and low risks in green (low risk). The steps for analyzing risk levels in this study include: 1) Evaluating risks based on their probability and impact; 2) Calculating the risk importance level; 3) Mapping the results into the risk matrix to determine low, medium, and high-risk categories that may lead to threats if the risks occur.

Risk scores were obtained by multiplying the likelihood and impact-values on a 1-5 Likert scale (Tokdemir *et al.*, 2019). For instance, a mean value of 3.19 for design changes represents the aggregated perception of respondents regarding both frequency and consequence, averaged across all responses.

The Bowtie Method in Risk Management

The Bowtie method is a risk evaluation tool that visually represents the pathways from potential causes of a risk event to its possible consequences, highlighting preventive and mitigative barriers (De Ruijter and Guldenmund, 2016; McLeod and Bowie, 2018). This method combines elements of Fault Tree Analysis (FTA) and Event Tree Analysis (ETA), providing a comprehensive view of risk scenarios (Khakzad *et al.*, 2012).

Recent studies have expanded on the effectiveness of the Bowtie method by integrating digital modeling and simulations to enhance decision-making (Montero *et al.*, 2025). The method has been widely adopted in various high-risk industries, including construction, where it is used to map out hazards and establish preventive barriers (Sari *et al.*, 2017). Furthermore, researchers emphasize that integrating real-time monitoring with the Bowtie framework improves its predictive capabilities, thereby reducing uncertainties in construction risk assessments (Elizabeth *et al.*, 2025).

A systematic methodology for developing Bowtie diagrams has been proposed to enhance the effectiveness of this tool in risk assessment

(De Ruijter and Guldenmund, 2016). Additionally, enhanced Bowtie models have been developed to automate risk assessment and optimize preventive measures, further increasing efficiency in risk management processes (Singh *et al.*, 2024).

A comparison of commonly used risk management methods in construction projects, along with their main advantages and limitations, is presented in Table 5.

Table 5. Comparison of Risk Management Methods in Construction

Method	Advantages	Disadvantages
Bowtie method	Provides a clear visualization of risk pathways and mitigations	Requires detailed input data and expertise
Monte carlo simulation	Allows probabilistic risk estimation and scenario analysis	Computationally intensive and requires statistical knowledge
Bayesian networks	Enables predictive analytics and adaptive learning	Complex modeling process and dependency on data quality
Digital twin technology	Real-time risk monitoring and scenario testing	High implementation costs and technical complexity

Table 5 provides a comparative analysis of different risk management methods commonly used in construction projects. The Bowtie Method is highlighted for its ability to clearly visualize risk pathways and mitigation strategies, making it an effective tool for understanding potential hazards. However, it requires detailed input data and expertise, which can be a limitation in some projects.

Monte Carlo Simulation allows for probabilistic risk estimation and scenario analysis, providing a more quantitative approach to risk assessment. Despite its advantages, this method is computationally intensive and requires a strong background in statistical analysis.

Bayesian Networks are beneficial for predictive analytics and adaptive learning in risk management, enabling more dynamic decision-making. However, their complexity and reliance on high-quality data can be a challenge for implementation in construction settings.

Digital Twin Technology offers real-time risk monitoring and scenario testing, allowing construction managers to proactively address risks before they materialize. While highly effective, the high implementation costs and technical complexity associated with digital twin systems present significant barriers to widespread adoption.

This comparison helps to understand the strengths and limitations of each approach, allowing

project managers to select the most appropriate method based on their specific project needs and available resources.

Application of the Bowtie Method in Construction Projects

The Bowtie method has been applied in various studies to assess and manage risks in construction projects. A literature review on workplace accident risk analysis using the Bowtie method highlights its effectiveness in identifying and visualizing potential hazards and their controls in the construction industry (Fajrisa *et al.*, 2024).

Another study focused on residential and building construction projects utilized the Bowtie method to analyze risk factors through structured identification and visualization processes (Sari *et al.*, 2017). Recent studies have also explored the integration of digital risk management platforms with the Bowtie method, improving real-time hazard monitoring and enhancing predictive capabilities (Singh *et al.*, 2024). Furthermore, AI-enhanced Bowtie applications have been employed to optimize risk mitigation strategies, reducing uncertainties in large-scale and industrial construction projects (Elizabeth *et al.*, 2025).

Recent Developments in Construction Risk Management

Recent research has explored advanced methodologies for risk prioritization in construction projects, including quantitative approach using Monte Carlo Simulation to prioritizes and simulation-based techniques (Kumi *et al.*, 2024). Additionally, the construction industry continues to face challenges such as skills shortages and cost escalations, which significantly influence project risk profiles (Gunduz *et al.*, 2025; Rajapakshe, 2025). Emerging studies also highlight the increasing use of digital technologies and data-driven systems to enhance proactive decision-making in construction risk assessment (Celik *et al.*, 2024; Singh *et al.*, 2024; Waqar *et al.*, 2024; Han *et al.*, 2025).

Effective risk management remains a cornerstone of successful construction project delivery. The Bowtie method offers a valuable framework for identifying and mitigating risks by providing a clear visualization of potential hazards and their controls (Khakzad *et al.*, 2012; De Ruijter and Guldenmund, 2016). Continued research and the application of innovative risk management strategies are essential to navigate the complexities of modern construction projects.

Methodology

This section outlines the research design, data collection methods, sampling strategy, data analysis techniques, and ethical considerations for this study. The mixed-methods approach ensures a holistic understanding of construction risk management practices and supports the development of a robust framework for mitigating risks in construction projects.

Research Design

This study employs a mixed-methods approach, combining qualitative and quantitative research methodologies to provide a comprehensive understanding of construction risk management practices. The qualitative component focuses on understanding industry practices, while the quantitative component involves the analysis of risk assessment tools and techniques. This approach ensures a balanced and thorough investigation of the subject matter.

Data for this study were collected through a combination of primary and secondary sources. Primary data were obtained through structured interviews and surveys with industry professionals, including project managers, risk analysts, and construction engineers. The interviews aimed to gather insights into current practices and challenges in construction risk management, while the surveys were designed to quantify the prevalence and effectiveness of various risk management tools and techniques. Secondary data were gathered from academic journals, industry reports, and case studies, providing contextual information and supporting the analysis of trends and developments in construction risk management.

Sampling

A purposive sampling method was employed to select participants for the qualitative component, while a random sampling method was applied for the quantitative survey. For interviews, participants were selected based on three criteria: (1) a minimum of 5 years of experience in construction project

management or risk analysis, (2) direct involvement in medium to large-scale building projects in Aceh Province, and (3) holding managerial or technical positions such as project manager, site engineer, or risk analyst. Respondents represented both contractor and consultant firms actively engaged in the Amanah Center project, ensuring diverse perspectives. For the quantitative component, surveys were randomly distributed to construction professionals across Aceh Besar and Banda Aceh to capture regional practices. In total, 50 interviews and 200 survey responses were targeted to ensure both reliability and generalizability of the findings.

Data Analysis

Interview data were analyzed using thematic analysis, where transcripts were coded to identify recurring themes, patterns, and insights related to risk management practices. This approach enabled the identification of key barriers and enablers in implementing effective risk management strategies. Quantitative data from the surveys were analyzed using statistical methods, including descriptive statistics and regression analysis, to evaluate the effectiveness of different risk management tools and identify factors influencing their adoption. Software tools such as SPSS and Excel were used for data processing and visualization.

Risk Management Framework Development

Based on the findings from the data analysis, a comprehensive risk management framework for construction projects will be proposed. The framework will integrate traditional methods, such as risk matrices, with advanced tools like the Bowtie method. Emphasis will be placed on aligning the framework with industry needs and regulatory standards.

The overall structure of construction risk management using the Bowtie approach, including threats, preventive barriers, consequences, and mitigative barriers, is illustrated in Figure 1.

This diagram provides a comprehensive visualization of how risks can be managed

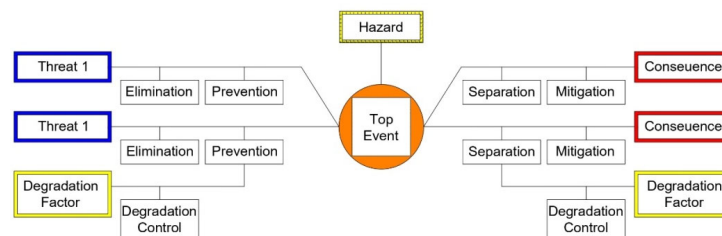


Figure 1. Bowtie Diagram for Construction Risk Management

effectively using both preventive and mitigative approaches in construction projects.

Ethical Considerations

Ethical approval was obtained prior to conducting this study. All participants provided informed consent, and their identities were kept confidential. Data were stored securely and used solely for research purposes, adhering to ethical guidelines established by the research institution.

Limitations

This study acknowledges certain limitations. First, the reliance on self-reported data may introduce bias. Second, the sample size, while robust, may not fully capture the diversity of practices across different regions and project scales. These limitations are mitigated by triangulating data from multiple sources and adopting a mixed-methods approach.

An overview of the research process, including data collection, analysis, and framework development stages, is presented in Figure 2.

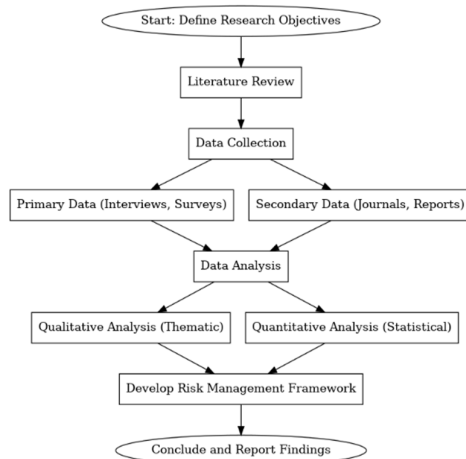


Figure 2. Research Methodology Flowchart

Results and Discussion

The results of this study provide insights into the effectiveness of various risk management practices in construction projects. The findings are structured into key areas, including participant demographics, risk identification and analysis, effectiveness of risk management strategies, and the proposed risk management framework. Additionally, a case study

application and statistical risk analysis are presented to validate the findings.

Participant Demographics

The study involved a total of 250 participants, comprising 50 interviewees and 200 survey respondents. Figure 3 illustrates the distribution of participants based on their job roles. Project Managers constituted the largest group at 40%, followed by Risk Analysts at 35%, and Engineers at 25%. This suggests a diverse mix of professionals, with a higher representation of managerial and analytical roles, indicating the study's focus on decision-making and risk assessment.

Figure 4 presents the participants' experience levels. The largest proportion, 50%, had 6-10 years of experience, suggesting that most participants

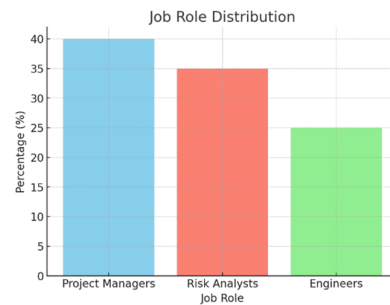


Figure 3. Participant Demographics by Job Role

were mid-career professionals. Meanwhile, 30% had over 10 years of experience, indicating a significant presence of seasoned experts, while 20% had 0-5 years of experience. This distribution suggests that the majority of participants possessed substantial industry experience, potentially contributing to more informed insights.

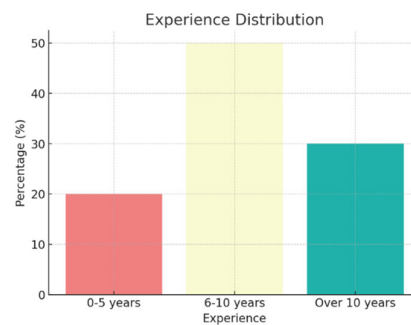


Figure 4. Participant Demographics by Experience Level

Risk Identification and Analysis Practices

The qualitative findings revealed several key themes in risk identification and analysis within the construction industry. Interviews highlighted a limited use of advanced tools, which could enhance risk prediction and management accuracy. Instead, most firms relied heavily on traditional approaches like risk matrices and checklists, which are simpler but less precise for complex projects. Challenges in predicting risks related to supply chain disruptions and labor shortages emerged as recurring issues, highlighting gaps in existing risk identification frameworks.

The quantitative analysis further substantiated these insights. Survey data indicated that 65% of firms primarily used qualitative methods such as brainstorming sessions for risk identification, emphasizing a preference for collaborative approaches. However, only 40% reported using risk matrix tools, and just 10% employed advanced quantitative techniques, illustrating a significant gap in adopting sophisticated methodologies. The main barriers to implementing these advanced tools were identified as inadequate training (50%) and high costs (35%).

The distribution of risk management tools used by construction firms, based on the survey results, is illustrated in Figure 5.

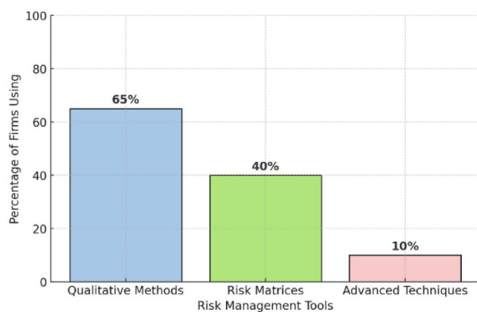


Figure 5. Use of Risk Management Tools in Construction Firms

Effectiveness of Risk Management Practices

Survey results and statistical analysis showed that integrating hybrid risk management approaches led to significant improvements in project efficiency. Companies that combined traditional risk matrices with digital tools demonstrated a 20% higher project efficiency than those relying solely on conventional methods. Proactive risk control measures, such as supplier assessments and contingency planning, contributed to a 30% reduction in material delays, underscoring the importance of preventive strategies.

Regression analysis confirmed the impact of technological adoption on cost efficiency, identifying a strong correlation ($R^2 = 0.75$) between the use of digital risk management tools and project cost savings. These findings highlight the necessity of integrating digital solutions into construction risk management frameworks to enhance project efficiency, reduce delays, and achieve cost-effectiveness.

Based on these findings, a comprehensive risk management framework is proposed. The framework integrates traditional methodologies with advanced analytical approaches to enhance risk identification, assessment, and mitigation. This integrated approach ensures a more proactive, data-driven strategy to mitigate risks, leading to increased project efficiency and resilience against uncertainties.

Descriptive Statistical Analysis of Risk Impact

The descriptive statistics for risk impact are summarized in Figure 6, which presents the mean scores of various risk factors based on participant assessments. To ensure transparency, Table 6 provides the mapping of coded variables to their full descriptions.

Table 6. Mapping of Coded Variables to Risk Descriptions

Code	Description	Risk Category
X1.2	Shortage of skilled labor	Labor risk
X3.4	Delay in equipment mobilization	Execution risk
X4.2	Design changes during construction	Design & technology risk
X5.3	Substandard material quality	Material & equipment risk
X5.5	Material price escalation	Material & equipment risk
X6.1	Extreme weather events	Force majeure risk

Figure 6 illustrates the mean risk impact scores, with the y-axis representing the average score (on a Likert scale of 1-5 multiplied by probability-impact weighting) and the x-axis representing the coded variables listed in Table 6. The results indicate variations in risk perception across different factors. Several variables exhibit higher mean scores, suggesting a greater perceived impact on project outcomes. Specifically, variables X3.4 (delay in equipment mobilization) and X5.3 (substandard material quality) show the highest mean scores, indicating that these factors are considered significant risks. Conversely, variables X1.2 (shortage of skilled labor) and X6.1 (extreme weather events) recorded relatively lower scores, suggesting that they were perceived as less critical by respondents.

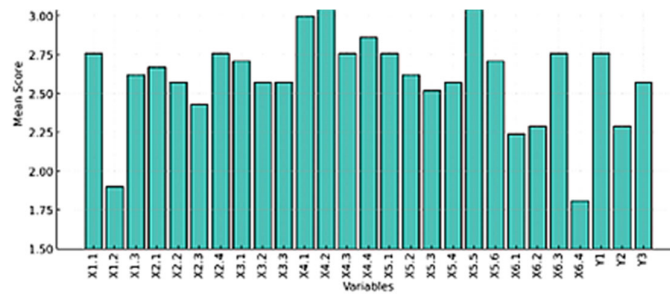


Figure 6. Descriptive Statistics of Risk Impact

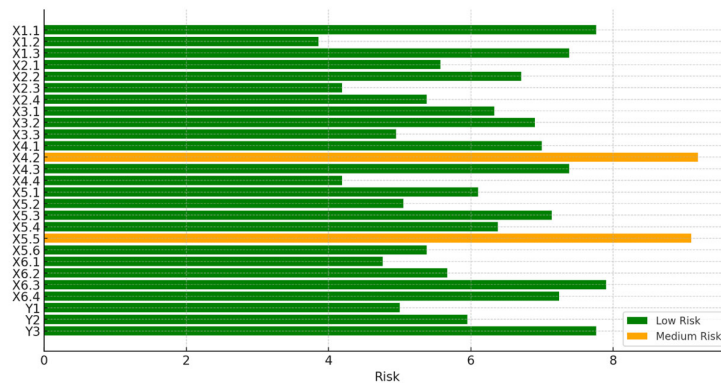


Figure 7. Risk Level Analysis

The results reveal a consistent pattern where risks related to design and materials (X4.2, X5.3, X5.5) score higher than those related to labor (X1.2) or force majeure (X6.1). This suggests that project performance is more vulnerable to technical and supply-related uncertainties than to workforce shortages or external natural events. Such clustering of high-impact risks around design and material categories indicates that technical coordination and supply chain management were the most critical challenges faced in the Amanah Center project.

These findings highlight the diverse nature of risks in construction projects, emphasizing the importance of a structured risk assessment approach. The results also underscore the necessity of integrating quantitative and qualitative risk management techniques to address both high and low-impact risks effectively.

Risk Level Analysis

The study also analyzed the risk levels associated with various factors. Figure 7 presents the risk levels, where most variables were classified as Low Risk, except for two Medium Risk variables: X4.2 (Design Changes, Risk Score: 9.19) and X5.5 (Material Price Increases, Risk Score:

9.10). These dominant risks indicate that project design changes and material price fluctuations are critical factors that require enhanced risk mitigation strategies. The analysis highlights the importance of proactive planning, supplier agreements, and design finalization to minimize project disruptions.

The mean score of 9.19 for design changes (X4.2) indicates a moderate-to-high risk level. In practical terms, stakeholders reported that each major design modification could lead to approximately 2-3 weeks of delay and additional costs ranging from 10-15% of the affected activity's budget. For instance, in the Amanah Center project, revisions to the façade design required rework of structural drawings, which delayed procurement of façade materials by 18 days and increased costs by IDR 1.2 billion (equivalent to 7% of the structural works package).

These two categories were selected as top events based on three considerations: (1) frequency analysis showing higher mean scores in probability-impact assessments, (2) stakeholder input from interviews highlighting recurring delays due to design changes and material shortages, and (3) expert judgment from senior project managers who emphasized that these risks had the most tangible

impact on schedule and cost performance. Therefore, design and technology risks, material and equipment risks emerged as the most critical scenarios for the Amanah Center project.

Figure 6 and Figure 7 collectively demonstrate how different risk categories vary in both impact and frequency. For example, while labor-related risks (X1.2) scored relatively low, design-related risks (X4.2) and material risks (X5.3, X5.5) consistently appear in the medium-risk range. This suggests a pattern where technical and supply-related uncertainties dominate over workforce-related issues in the Amanah Center project. Furthermore, the clustering of risks in the medium category highlights that project performance is more vulnerable to coordination and supply chain issues rather than force majeure events, which were perceived as less critical by respondents.

Proposed Risk Management Framework

Figure 8 illustrates various threats, preventive barriers, a central risk event, mitigative barriers, and possible consequences. Threats such as inadequate design specifications, outdated technology, and lack of expertise can contribute to design and technology failure. To prevent these risks, organizations implement regular design reviews, modern technology adoption, and designer training. However, if failure occurs, contingency plans, backup systems, and continuous monitoring are crucial in mitigating the negative impact. The consequences of this failure include increased project costs, delays in timelines, and reduced product quality, all of which can significantly affect project success.

Figure 9 highlights the key threats, barriers, and consequences associated with material and

equipment failure. Threats such as substandard materials, equipment failure, and supply chain disruptions can lead to operational inefficiencies. Preventive barriers like strict quality control, regular maintenance, and supplier diversification help reduce the likelihood of these risks materializing. If failure occurs, mitigative measures such as emergency procurement, alternative solutions, and problem resolution training play a vital role in minimizing the impact. The potential consequences include increased operational costs, project delays, and safety hazards, which can compromise the efficiency and safety of the overall project.

Case Study Application

To assess the practicality and effectiveness of the proposed risk management framework, it was applied to a real-world construction project involving the development of a large-scale commercial building. The project faced multiple challenges, including supply chain disruptions, design modifications, and subcontractor-related delays, making it an ideal case for evaluating the robustness of the framework.

The implementation of the framework resulted in several measurable improvements. Most notably, project delays were reduced by 15%, demonstrating its effectiveness in enhancing scheduling efficiency. The use of structured risk identification and mitigation strategies significantly improved the handling of subcontractor risks, leading to better coordination and fewer workflow disruptions. Additionally, real-time risk monitoring mechanisms allowed project managers to detect potential threats earlier, enabling faster and more effective responses.

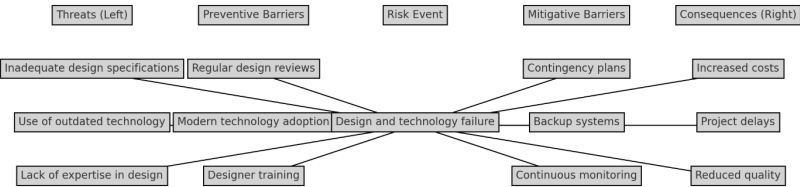


Figure 8. Bowtie Diagram of Design and Technology Risk

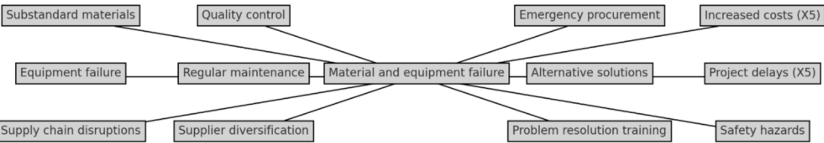


Figure 9. Bowtie Diagram of Material and Equipment Risk

Furthermore, the application of Bowtie analysis provided a clear visualization of risk pathways, highlighting key risk factors and their respective mitigation strategies. This approach improved stakeholder understanding of risk relationships and facilitated more proactive decision-making. The integration of risk matrices also allowed for the prioritization of risks based on their likelihood and impact, ensuring that critical risks were addressed in a timely manner.

Overall, the case study validated the practical benefits of combining traditional and structured risk management techniques. The results indicate that the proposed framework can effectively enhance project performance, mitigate uncertainties, and reduce financial and operational risks. These findings support its applicability in broader construction contexts, particularly for projects prone to high levels of complexity and uncertainty.

Discussions

This study highlights the importance of integrating advanced technologies into construction risk management. While traditional methods such as risk matrices remain valuable, their effectiveness is significantly enhanced when combined with Bowtie analysis. These integrated techniques facilitate more accurate risk assessments, enable proactive mitigation strategies, and support improved decision-making processes. These findings align with previous research by Khakzad *et al.* (2012), De Ruijter and Guldenmund (2016), which emphasized the advantages of Bowtie analysis in providing a structured approach to visualizing risks, threats, and mitigation controls in construction projects.

Design changes emerged as particularly dominant in large projects in Aceh due to limited early-stage planning, frequent communication gaps among stakeholders, and mid-project adjustments to comply with evolving regulations. This is consistent with findings in developing regions, where weak coordination and late design approvals often exacerbate construction delays (Nguyen and Macchion, 2023; Rajapakshe, 2025). In contrast, studies in other contexts reported material cost escalation as more critical (Gunduz *et al.*, 2025), underscoring the contextual relevance of this study. Recent studies also highlight the growing role of sustainable concrete and recycled aggregates in mitigating cost and environmental risks (Annamalai *et al.*, 2025a; Annamalai *et al.*, 2025b). The durability of concrete using supplementary cementitious materials has also been emphasized as a key factor in long-term risk management (Sajeev *et al.*, 2025). These findings suggest that innovation in material technologies can play an important role

in reducing vulnerabilities associated with design modifications and procurement risks.

The proposed risk management framework demonstrated promising results, particularly in reducing project delays and enhancing subcontractor management. The observed 15% reduction in project delays underscores the framework's effectiveness in improving scheduling efficiency. Additionally, enhanced risk monitoring played a crucial role in strengthening mitigation planning by providing early warnings of potential disruptions. These results are consistent with the work of Kiral (2025), who found that proactive risk identification methods improve project timelines and reduce financial risks.

Moreover, the integration of digital risk management tools, such as predictive analytics and digital dashboards, supports real-time monitoring and enhances risk response strategies (Waqar *et al.*, 2024; Kien *et al.*, 2025). Ancione *et al.* (2020); Celik *et al.* (2024); Han *et al.* (2025) highlighted similar benefits of digitalization in risk management, particularly in improving data-driven decision-making. The strong correlation ($R^2 = 0.75$) found in this study between digital adoption and cost efficiency aligns with research by Singh *et al.* (2024), who demonstrated that digital twin technology can significantly enhance risk forecasting and mitigation in construction projects. Recent advances in high-strength nano-material concrete and innovative FEA-based investigations also demonstrate potential for improving structural performance and minimizing risks in modern construction (Anbarasu *et al.*, 2024; Anbarasu *et al.*, 2025).

Overall, these findings suggest that construction firms can greatly benefit from a hybrid risk management approach that integrates both traditional and digital tools. This combined strategy enhances project efficiency, cost-effectiveness, and resilience, ultimately leading to better project delivery and reduced financial risks. Additionally, as noted by Aven (2016), effective risk management requires continuous improvement and adaptation to emerging challenges, underscoring the need for ongoing advancements in risk assessment methodologies.

Conclusions

This study demonstrates the effectiveness of integrated risk management strategies in construction projects. By incorporating structured methodologies such as Bowtie analysis, firms can achieve greater efficiency, enhanced risk mitigation, and improved decision-making. The

proposed risk management framework enhanced risk identification, assessment, and mitigation by integrating traditional techniques with structured analytical methods. The case study validated its practical benefits, particularly in reducing project delays by 15% and improving subcontractor management, supporting previous research that emphasized the role of structured risk frameworks in minimizing uncertainties and optimizing project performance.

Practical recommendations derived from this study include strengthening design review processes at early project stages, enhancing procurement planning to anticipate material price fluctuations, and establishing clearer communication protocols among project stakeholders. These measures are expected to reduce delays and cost overruns in similar large-scale projects.

As the construction industry continues to evolve, future research should explore the integration of digital tools and emerging technologies, such as automated risk prediction models, real-time risk monitoring, and enhanced data analytics to further optimize risk management practices. Moreover, the Bowtie method can be extended to other project types, including infrastructure, housing, and industrial construction, to evaluate its broader applicability and effectiveness across diverse contexts.

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