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Construction Material Supply Chain Risk Analysis on Dam Consolidation Projects at Miu River and Tuva River Using the Monte Carlo Simulation Model

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Abstract
Risk Analysis of Supply Chain Material Construction in Miu and Tuva River Consolidation Dam Projects Using Monte Carlo Simulation Model (guided by Fahirah and I Gede Tunas).
Earthquakes, landslides, and flash floods that occurred in Central Sulawesi, especially in Sigi Regency, have caused an increase in sedimentation in the Palu Watershed and damage to various infrastructures. As an effort to control sediment and mitigate flooding, the government is implementing in the Miu River and Tuva River Consolidation Dam Project. In its implementation, the construction project has a complex supply chain and is vulnerable to various risks that can affect project performance. This research aims to identify and assess material construction supply chain risks in the Miu River and Tuva River Consolidation Dam Projects and analysis their impacts using the Monte Carlo Simulation model. The research is carried out through risk identification based on the stages of the construction supply chain which includes demand, process, supply and control. Data were obtained through literature studies, field observations, interviews, and the distribution of questionnaires to parties involved in the project. The results of the research identified the dominant risks in the material construction supply chain and provided an overview of the probability due to supply chain disruptions. According to the result of Monte Carlo simulations and risk sensitivity analysis, the most influential dominant risks were delays in material delivery due to expedition 17.3%, procurement delays of 14.5%, changes in demand during the process of running by 13.6%, difficulty in finding materials due to limited stock of 13.0% and inaccurate demand (incorrect estimation of material volume) of 7.0%

Keywords: *Risk, Supply Chain, Construction Projects, Simulation, Monte Carlo.*

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I. INTRODUCTION

The Mw 7.4 earthquake that struck Central Sulawesi, Indonesia, on September 28, 2018, caused significant landscape changes, landslides, and severe sedimentation within the Palu River Basin. These conditions increased the occurrence of flash floods, resulting in substantial damage to infrastructure, agricultural land, and residential areas, particularly along the Miu and Tuva Rivers in Sigi Regency. In response, the Indonesian Ministry of Public Works and Housing initiated the Consolidation Dam Project through the Sulawesi III River Basin Agency to reduce flood hazards and control sediment transport.

The success of this construction project largely depends on effective construction supply chain management. Construction supply chains involve multiple stakeholders, including project owners, contractors, suppliers, and subcontractors, making them highly complex and vulnerable to uncertainty. Risks such as material procurement delays, transportation disruptions, design changes, equipment failures, and price fluctuations can significantly affect project cost, schedule, and quality.

Therefore, early identification and analysis of supply chain risks are essential to minimize their impact on project performance. This study aims to identify and analyze material supply chain risks in the Miu and Tuva River Consolidation Dam Project in Sigi Regency and to provide a basis for developing effective risk mitigation strategies that support successful project delivery.

The objectives of this study are as follows:

1. Analyze the risk level of the construction material supply chain in the Miu and Tuva River Consolidation Dam Project, Sigi Regency.
2. Apply Monte Carlo simulation to evaluate the impact of construction material supply chain risks on the performance of the Miu and Tuva River Consolidation Dam Project

II. LITERATURE REVIEW

2.1. CONSTRUCTION PROJECT

A construction project is a temporary and unique series of interrelated activities undertaken to deliver a building or infrastructure within predetermined constraints of time, cost, and quality. Construction projects involve multiple resources and stakeholders, requiring effective coordination and management to achieve the project objectives. According to Dipohusodo (1995), a project is an organized effort that utilizes available resources to accomplish specific goals within an agreed timeframe.

2.2. CONSTRUCTION PROJECT PHASE

Construction projects generally consist of several sequential phases, as follows:

1. Planning Phase

The planning phase aims to establish the project objectives and prepare the necessary resources before implementation. The primary activities include:

a. Assisting the project owner in developing the project program based on the owner's requirements, objectives, and existing constraints. This includes collecting, preparing, and analyzing the necessary data covering administrative, technical, financial, and legal aspects. In addition, cost analyses are conducted for the proposed systems developed by the design consultant, followed by evaluations and recommendations for system improvements or modifications supported by preliminary cost analyses.
b. Assisting the project owner in selecting project participants according to the qualifications and competencies required for the project.

2. Design Phase

The design phase consists of several sub-stages, namely preliminary design, design development, final design, preparation of construction documents, and the tendering process.

a. Preliminary Design
b. Design Development
   During the design development stage, the following activities are undertaken:
c. Final Design and Preparation of Construction Documents

3. Construction Phase

The construction phase primarily focuses on project control to ensure that project objectives related to time, cost, and quality are achieved. Major activities include:

a. Coordinating the activities of contractors, design consultants, and the project owner to maintain effective control over project schedule, budget, and quality.
b. Assigning qualified field personnel with sufficient authority to supervise and control project implementation.
c. Organizing coordination meetings between the project owner and the construction management team to discuss pre-construction issues, project progress, scheduling, procedures, and site-related problems.
d. Monitoring the overall project schedule, project milestones, contractor activities, long-lead material procurement, and the planned occupancy schedule of the completed facility.
e. Reviewing construction schedules, monitoring incomplete or delayed activities, and ensuring alignment with the overall project completion target.
f. Preparing concise monitoring reports and documenting all schedule revisions and project changes.
g. Conducting regular project coordination meetings involving the contractor, construction management team, design consultant, and project owner to facilitate communication, resolve implementation issues, and ensure effective project execution.

2.3 CONSTRUCTION PROJECT RISK

Risk refers to the possibility of an event or occurrence that may adversely affect an organization or business, where the occurrence cannot be predicted with certainty (Latifiana, 2017). The Indonesian Bankers Association (Ikatan Bankir Indonesia) summarizes several definitions of risk proposed by experts as follows:

1. According to the Australian Risk Management Standard, risk is the chance that an event will occur and have an impact on the achievement of objectives.
2. According to David McNamee and Georges Selim, risk is a concept used to describe the uncertainty of an event and/or its consequences that may materially affect the achievement of an organization's objectives.
3. According to The Institute of Internal Auditors (IIA), risk is the uncertainty of an event that may influence the achievement of organizational objectives. Risk is measured in terms of its likelihood of occurrence and its consequences.
4. According to the Committee of Sponsoring Organizations of the Treadway Commission (COSO), risk is defined as the possibility that an event will occur and adversely affect the achievement of organizational objectives.

5. According to SNI ISO 31000, risk is the effect of uncertainty on organizational objectives, which may have either negative or positive impacts. However, particular attention should be given to risks with negative impacts, as they may hinder the achievement of both short-term and long-term organizational goals.

Based on the definitions above, risk can be defined as the possibility of an uncertain event or condition that may significantly affect an organization or company and potentially result in future losses or impede the achievement of its objectives

2.4 RISK MANAGEMENT STRATEGIES

Several risk management strategies have been widely recognized as effective approaches to minimizing potential losses within organizations.

1. Risk Identification
   Risk identification constitutes the initial stage of the risk management process. Organizations are required to systematically identify potential risks that may arise across all business functions, including operational activities, financial management, information technology, corporate reputation, as well as regulatory and governmental policy changes. To ensure a comprehensive assessment, all organizational departments should participate in the risk identification process, thereby enabling a holistic understanding of potential threats.
   Following identification, each risk should be evaluated according to its potential impact and likelihood of occurrence. Impact refers to the magnitude of losses that may result if a risk materializes, whereas likelihood represents the probability of its occurrence. This evaluation enables organizations to prioritize significant risks and develop appropriate response strategies.
2. Risk Treatment
   The second strategy involves implementing appropriate risk treatment measures after risks have been identified and assessed. Risk treatment generally consists of three complementary approaches.
   First, preventive measures are implemented to reduce the likelihood of risk occurrence. For example, installing surveillance systems can minimize the risk of theft.
   Second, mitigation measures are adopted when risks cannot be completely avoided. These measures aim to reduce the severity of adverse consequences. For instance, organizations may insure their assets to minimize financial losses resulting from asset damage or theft.
   Third, recovery measures are established to facilitate business continuity following the occurrence of a risk event. Recovery planning enables organizations to restore normal operations as quickly as possible. Routine data backup, for example, helps reduce the impact of system failures and data loss.
3. Risk Performance Evaluation
   Continuous evaluation of risk management performance is essential to determine whether implemented strategies remain effective. Organizations should conduct periodic internal and external audits to assess the adequacy and effectiveness of their risk management systems.
   The results of these evaluations provide valuable feedback for improving existing risk management practices. Furthermore, periodic evaluations enable organizations to identify emerging risks and implement appropriate preventive measures before significant impacts occur.
4. Training and Education
   Employee training and education play a crucial role in strengthening organizational risk management capabilities. Employees should be equipped with sufficient knowledge to recognize potential risks arising from their daily activities and to report them appropriately to management. In addition, training programs should develop employees' competencies in implementing effective risk management practices. Increased awareness and competence among employees contribute significantly to reducing organizational vulnerability to risk.
5. Collaboration and Partnerships
   Collaboration with external stakeholders represents another important risk management strategy. Organizations may establish partnerships with companies operating within the same industry or with other relevant stakeholders to improve risk management effectiveness. Such collaborations may include sharing technological resources to reduce operational costs, exchanging information regarding emerging risks, or forming strategic consortia to address highly complex risks. Through collaborative initiatives, organizations can improve operational efficiency while reducing potential losses associated with risk events.
   Risk analysis aims to determine the influence of risk factors on a system by examining risk events and their cumulative effects on one or more project objectives. Grouping related risk events facilitates more effective long-term risk mitigation than addressing individual risks separately, thereby reducing excessive project-level micro-management. Various techniques have been proposed in the literature for project risk analysis, including probability and impact matrices, system reliability estimation, fault tree analysis (FTA), event tree analysis (ETA), sensitivity analysis, and simulation methods.

Risk evaluation is conducted to prioritize identified risks and determine the most appropriate mitigation strategies based on previous experience, lessons learned, organizational knowledge, best practices, and established industry standards (Ahmed et al., 2003a, 2003b). During this stage, strategic, financial, and scheduling aspects of a project are considered when selecting suitable mitigation alternatives. Commonly applied risk evaluation techniques include decision tree analysis, portfolio management, and multi-criteria decision-making (MCDM) methods.

Risk events adversely affect project objectives when unexpected circumstances lead to unfavorable outcomes. Consequently, risk management seeks to systematically identify controllable events and establish appropriate response plans before adverse consequences occur. A reactive approach, also referred to as a feedback approach, focuses on implementing mitigation measures after a risk event has occurred and is typically associated with contingency planning. Conversely, a proactive or feedforward approach emphasizes preventive actions based on the anticipated probability of risk occurrence, such as purchasing insurance or implementing preventive controls (Kartam, 2001; DeMaio et al., 1994). Modern risk management frameworks integrate both reactive and proactive approaches to reduce the likelihood of risk occurrence, minimize its impact, transfer risk where appropriate, and retain acceptable levels of residual risk (AS/NZS 4360:1999).

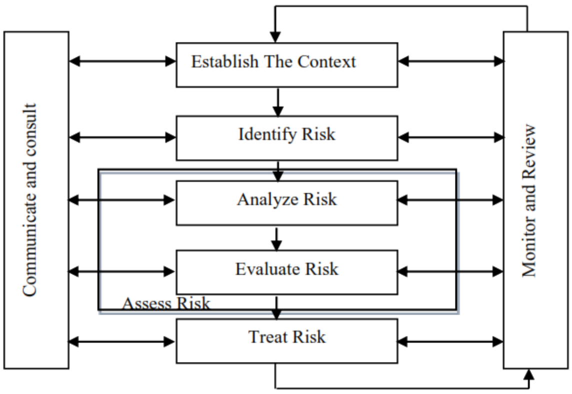

Figure 1. Risk Management Framework

Source: AS/NZS 4360:1999 Risk Management Standard.

2.5 SUPPLY CHAIN IN THE CONSTRUCTION INDUSTRY

Supply chain activities in the construction industry are inherently exposed to various risks throughout project execution. Common supply chain risks include delivery delays, material availability, material quality issues, price fluctuations, project management failures, regulatory changes, financial risks, environmental risks, technological risks, and human resource-related risks. According to Behera et al. (2015), the characteristics of construction project supply chains are influenced by several factors, including customer influence, industry fragmentation, the number and diversity of stakeholders, buyer–supplier relationships, temporary multi-organizational structures, make-to-order supply chain configurations, opportunities for collaboration, and cyclical demand patterns resulting from repeated procurement activities.

The occurrence of these risks may adversely affect supply chain management performance and ultimately lead to project delays. Christopher (2011) identified several primary sources of risk that influence supply chain networks and contribute to an organization's overall risk profile.

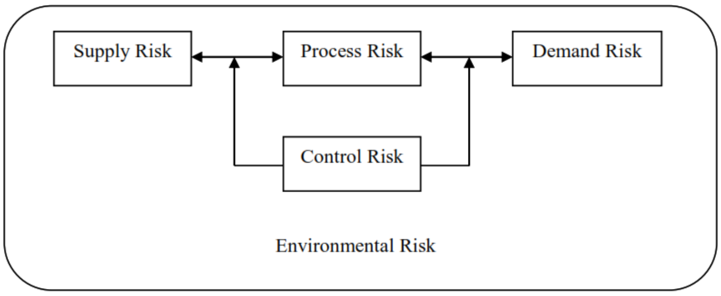

Figure 2. Model of Supply Chain Uncertainty Drivers

Adapted from Christopher, M. (2011). Logistics & Supply Chain Management.

2.6 MONTE CARLO SIMULATION

Simulation is an experimental approach used to analyze systems when direct observation of real-world systems is impractical or impossible. It is particularly valuable when mathematical analytical methods are limited due to the complexity of the system or the difficulty of validating mathematical models that accurately represent system behavior (Yuwana, 2017). According to Kelton, Sadowski, and Zupick (2015), simulation is a method and application used to imitate the behavior of real-world systems, typically through computer-based models that replicate system operations.

Monte Carlo simulation is a probabilistic analytical technique that employs randomly generated input values to produce probability-based statistical outcomes, enabling decision-makers to evaluate the effects of uncertainty on system performance. This method has been widely applied in project evaluation, project management, cost analysis, and numerous other engineering and management disciplines.

Widya (2017) defined Monte Carlo simulation as a probabilistic simulation method that approximates the solution of complex problems through repeated random sampling. In this approach, each variable within the model is represented by a probability distribution, reflecting the range and likelihood of its possible values. The simulation repeatedly samples random values from these probability distributions—often thousands of iterations depending on the complexity of the system—to estimate the range of possible outcomes and their associated probabilities.

Conventional project scheduling techniques, such as the Critical Path Method (CPM) and the Precedence Diagram Method (PDM), generally assume deterministic activity durations. Consequently, these methods may not accurately represent actual project conditions, where activity durations are subject to significant uncertainty and risk. Monte Carlo simulation addresses this limitation by explicitly incorporating uncertainty into project scheduling models, thereby providing probabilistic estimates of project completion time rather than single deterministic values.

One of the principal advantages of Monte Carlo simulation is its ability to systematically quantify uncertainty and evaluate the likelihood of different project outcomes. By modeling uncertainty explicitly, project managers can better identify potential schedule and cost risks, improve decision-making, and develop more effective mitigation strategies. Consequently, Monte Carlo simulation supports the optimization of project performance with respect to time, resource utilization, and project costs.

III. RESEARCH METHODOLOGY

3.1. RESEARCH LOCATION

The study was conducted at the Miu River and Tuva River Dam Consolidation Project located in Sigi Regency, Central Sulawesi, Indonesia, as illustrated in Figure 3.3. The research was carried out over an eight-month period, from December 2024 to July 2025.

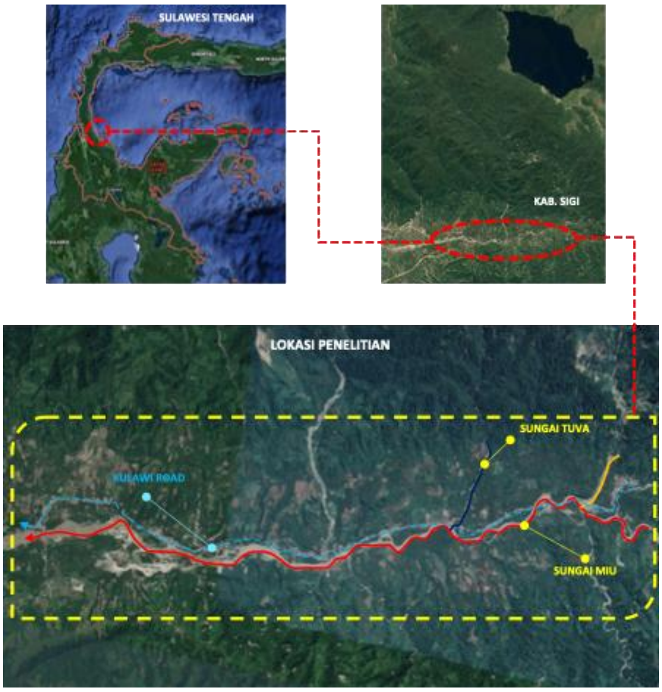

Figure 3. Research Location

3.2. DATA COLLECTION

In this study, primary data were collected through interviews and a structured questionnaire distributed via Google Forms to selected respondents from PT Adhi Karya (Persero) Tbk. Prior to data collection, approval was obtained from the project management while the project was in progress.

Secondary data were obtained from the project's general documentation and administrative records. Following the questionnaire survey, semi-structured interviews were conducted to validate and determine appropriate risk response strategies for the identified and assessed risks. These interviews involved key project personnel, including the Project Manager, Project Commercial Manager, and Risk Officer, who were responsible for project risk management and decision-making.

Table 1. List Supply Chain Risk Register

No.	List Supply Chain Risk	Supply Chain Cycle			
		Demand	Process	Supply	Control
1	Inaccurate demand forecasting (incorrect material quantity estimation)	✓			
2	Inappropriate demand timing	✓			
3	Incomplete demand specification and documentation	✓			
4	Frequent changes in material demand	✓			
5	Poor cross-functional coordination in scheduling and demand planning	✓			
6	Difficulty in procuring materials due to limited availability	✓			
7	Additional material orders resulting from design or functional changes	✓			
8	Delayed material procurement due to financial constraints	✓			
9	Materials supplied without the required mining permits (IUP)	✓			
10	Delays in material procurement		✓		
11	Supplier production disruptions		✓		
12	Non-conforming material quality		✓		
13	Changes in demand during project execution		✓		
14	Material price fluctuations		✓		
15	Repeat orders due to insufficient material quantities		✓		
16	Repeat orders due to material damage or loss in storage		✓		
17	Additional orders resulting from increased work volume		✓		
18	Delivery delays caused by inadequate storage capacity		✓		
19	Transportation equipment failure during project execution		✓		
20	Material delivery delays caused by freight forwarding services			✓	
21	Material delivery delays due to adverse weather or sea storms			✓	
22	Delays in unloading materials at the transit location (Palu Port)			✓	
23	Delivery delays due to limited supplier inventory			✓	
24	Logistics or transportation access disruptions			✓	
25	Unstable transportation costs			✓	
26	Limited availability of material transportation equipment			✓	
27	Unsynchronized information regarding inventory, deliveries, or material usage across functional units				✓
28	Discrepancies between purchase orders, delivery records, and actual material usage				✓
29	Recurring operational issues that are not addressed systematically				✓
30	Insufficient personnel training in control systems				✓
31	Limited capability of on-site logistics personnel in providing accurate information				✓

No.	List Supply Chain Risk	Supply Chain Cycle			
		Demand	Process	Supply	Control
32	Order modifications resulting from inaccurate material requirement calculations				✓
33	Delayed payment of outstanding liabilities				✓

The identified risks presented above were subsequently examined through questionnaires and semi-structured interviews conducted with the project management team to perform a risk screening process. This screening was undertaken to refine the preliminary risk register and focus on the risks that are most relevant to the construction material supply chain cycle. The screening process was considered necessary because several identified risk factors are difficult to quantify and systematically assess in terms of their probability of occurrence and their potential impact on project time and cost performance.

3.3. DATA ANALYSIS

3.3.1. RISK ANALYSIS

At this stage, a quantitative risk analysis was conducted to assess the severity (impact) and probability (occurrence) of identified risks in relation to the established project objectives. The primary objective of the risk analysis was to distinguish critical risks from those considered insignificant, thereby enabling the prioritization of risk management efforts. Information used in the analysis was obtained from project documentation, relevant project experience, established industry practices, published literature, consultations with the project team, and expert judgment provided by specialists.

The risk analysis employed a quantitative approach, which provides a systematic and objective assessment of identified risks. This approach is suitable for evaluating a wide range of risk scenarios and supports the prioritization of risks based on their likelihood of occurrence and potential consequences. The analysis focuses on two principal components: (1) the likelihood of risk occurrence and (2) the severity of its consequences. These quantitative assessments were subsequently used as input variables for the Monte Carlo simulation model. The simulation generated probabilistic estimates of project outcomes, including confidence (certainty) levels and contingency requirements associated with project uncertainty.

3.3.2. MONTE CARLO SIMULATION

At this stage, risk evaluation was performed using the Monte Carlo simulation approach to assess the uncertainty associated with construction project risks. Historical project data, represented by the probability and impact scores obtained from the questionnaire survey, were used as the input parameters for the simulation model. The Monte Carlo simulation generated probabilistic estimates of project risk and produced the corresponding risk levels based on the combined effects of risk probability and impact. These results provided a quantitative basis for evaluating project uncertainty and supporting risk-informed decision-making.

3.3.3 RISK MITIGATION

a. Risk Level Assessment
In the final stage of the analysis, risks were assessed based on the cumulative results generated from the Monte Carlo simulation. The resulting risk levels provide valuable information for project managers and decision-makers in determining appropriate strategies for responding to risks that may affect project schedule and cost performance. The risk assessment report serves as a decision-support tool by identifying priority risks and recommending strategies to minimize adverse impacts while maximizing potential opportunities.

b. Risk Response
Risk mitigation strategies were developed through brainstorming sessions with stakeholders directly involved in the construction project supply chain. In this study, the brainstorming process was conducted with the Project Manager, who possesses comprehensive knowledge of project execution and supply chain management practices. Based on this discussion, appropriate risk responses were determined in accordance with commonly accepted risk management techniques.
The risk response strategies adopted in this study include:

1. Risk Avoidance – eliminating or modifying project activities to prevent the occurrence of the identified risk.
2. Risk Transfer – shifting the responsibility or financial consequences of a risk to a third party, such as through insurance, contractual agreements, or outsourcing.
3. Risk Mitigation – implementing measures to reduce either the likelihood of occurrence or the potential impact of the identified risk.
4. Risk Acceptance – acknowledging the existence of a risk and deciding to accept its consequences when the potential impact is considered acceptable or when mitigation is not economically justifiable.

IV. RESULTS AND DISCUSSION

4.1. OVERVIEW OF THE RESEARCH FINDINGS

This study investigates material supply chain risks in the Miu River and Tuva River Dam Consolidation Project using the Monte Carlo simulation method. Risk identification was conducted through a structured questionnaire developed from interviews with key project stakeholders, including the Project Manager, Procurement Manager, Construction Manager, Commercial Manager, QHSE Manager, Procurement Officer, Expeditor Officer, Supervisor, Quality Control, and Risk Officer.

The identified risks were classified into four dimensions: Demand, Process, Supply, and Control. A total of 33 material supply chain risk variables were identified and assessed based on their likelihood and impact on project performance. These risk variables served as the input for the Monte Carlo simulation to determine cumulative risk levels and identify priority risks for mitigation. The complete list of identified risks is presented in Table 2.

Table 2. List of Identified Material Supply Chain Risks

Risk Code	Material Supply Chain Risk
D1	Inaccurate demand forecasting (incorrect estimation of material quantities)
D2	Mismatch in demand timing
D3	Insufficient information in material request documentation
D4	Fluctuating material demand
D5	Lack of cross-functional coordination in demand scheduling and quantity planning
D6	Difficulty in sourcing materials due to limited availability
D7	Additional material orders due to changes in project functional requirements
D8	Delayed material delivery caused by financial cash flow constraints
D9	Procurement of materials without the required mining permit (IUP)
P1	Procurement delays
P2	Supplier production disruptions
P3	Material quality does not meet specifications
P4	Changes in demand during project execution
P5	Material price fluctuations
P6	Reordering due to insufficient materials to meet project requirements
P7	Reordering due to material damage or loss in storage
P8	Additional material orders due to increased work volume
P9	Delivery delays caused by inadequate storage capacity
P10	Transportation equipment breakdown during project execution
S1	Material delivery delays caused by freight forwarding services
S2	Material delivery delays due to adverse weather or sea storms
S3	Delays in unloading materials at the transit port (Palu Port)
S4	Material delivery delays due to limited supplier inventory
S5	Logistics or transportation access disruptions
S6	Unstable transportation costs
S7	Limited availability of material transportation vehicles
C1	Lack of synchronization of material inventory, delivery, and usage information across project functions
C2	Discrepancies between procurement, delivery, and actual material usage records
C3	Recurring issues are not addressed systematically
C4	Inadequate personnel training in control systems

Risk Code	Material Supply Chain Risk
C5	Insufficient capability of on-site logistics personnel in providing accurate information
C6	Changes in material orders due to inaccurate material requirement calculations
C7	Delayed payment of overdue liabilities

The questionnaire data were processed using Microsoft Excel to determine the probability and impact of each identified risk. The probability values ranged from 0.10 to 0.69, while the impact values ranged from 10% to 69%, as summarized in Table 3. The risks with the highest probability and impact include material delivery delays due to freight forwarding services (S1), procurement delays (P1), changes in demand during project execution (P4), difficulty in sourcing materials due to limited availability (D6), and inaccurate demand forecasting caused by incorrect material quantity estimation (D1).

4.2. MONTE CARLO SIMULATION

The questionnaire data were analyzed using Oracle Crystal Ball with 20,000 Monte Carlo simulation iterations. The simulation results are presented in 4. The output indicates a P5 value of 154.5, meaning that only 5% of the simulated outcomes fall below this value. The P50 value of 166.4 represents the median of the simulation results, while the P95 value of 178.4 indicates that 95% of the simulated outcomes do not exceed this value. The simulation also produced a minimum value of 139.4 and a maximum value of 193.4.

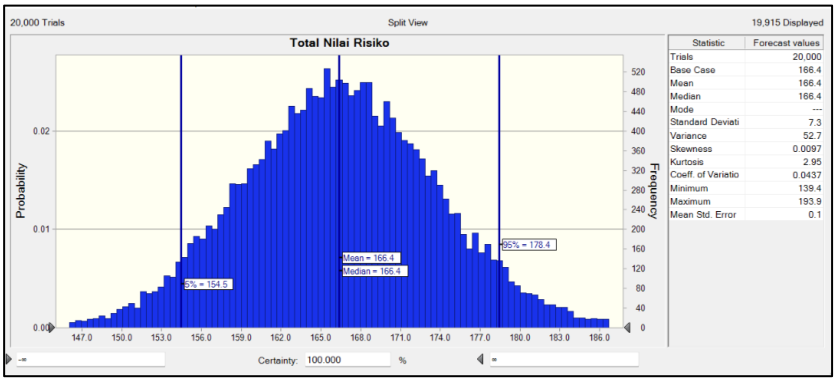

Figure 4. Monte Carlo Simulation Results

Based on the responses from 10 experts, where the maximum probability and impact scores were both 5, the Risk Index was calculated using the product of the probability and impact scores. The Risk Index obtained from the Monte Carlo simulation is expressed as follows:

The Monte Carlo simulation produced a Risk Index of 66.56%, indicating that the overall material supply chain risk of the project falls within a moderately high risk level.

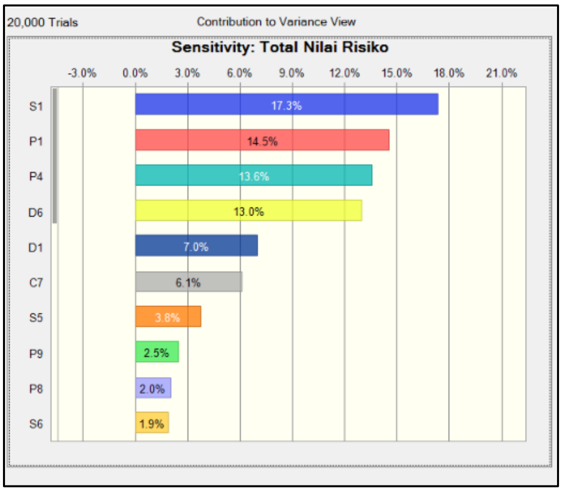

Figure 5. Risk Contribution Percentages

The Monte Carlo simulation ranked the identified risks according to their contribution to overall project delays and supply chain performance. The sensitivity analysis identified the five most influential risks, as illustrated in Figure 5: material delivery delays due to freight forwarding services (S1) (17.3%), procurement delays (P1) (14.5%), changes in demand during project execution (P4) (13.6%), difficulty in sourcing materials due to limited availability (D6) (13.0%), and inaccurate demand forecasting caused by incorrect material quantity estimation (D1) (7.0%).

These findings indicate that risks associated with material transportation and procurement have the greatest influence on project supply chain performance, particularly in projects located in geographically challenging areas with limited logistics accessibility, such as the Miu River and Tuva River Dam Consolidation Project.

Table 3. The complete risk values.

Risk Description	Risk Code	Rank	Contribution
Material delivery delays due to freight forwarding services	S1	I	17.3%
Procurement delays	P1	II	14.5%
Changes in demand during project execution	P4	III	13.6%
Difficulty in sourcing materials due to limited availability	D6	IV	13.0%
Inaccurate demand forecasting (incorrect estimation of material quantities)	D1	V	7.0%

4.3 DISCUSSION

Based on questionnaire responses from 10 management representatives of PT Adhi Karya (Persero) Tbk involved in the Miu River and Tuva River Dam Consolidation Project, the identified risks were classified into four dimensions: Demand (D), Process (P), Supply (S), and Control (C). Respondents evaluated each risk using a five-point Likert scale for both likelihood and impact (1 = very low; 5 = very high). The average probability and impact scores were subsequently used as inputs for the Monte Carlo simulation in Oracle Crystal Ball.

The Monte Carlo simulation was performed through repeated iterations to quantify the uncertainty associated with material supply chain risks. The simulation mean represents the most likely project risk level, whereas the higher percentile values (e.g., P90 and P95) indicate the contingency required to address uncertainty during project execution.

The sensitivity analysis revealed that material delivery delays caused by freight forwarding services (S1) contributed the highest risk (17.3%), mainly due to the project's dependence on materials supplied from outside the region. This was followed by procurement delays (P1) (14.5%) and changes in demand during project execution (P4) (13.6%), which were primarily associated with inadequate coordination between the construction and logistics teams. In the Demand category, difficulty in sourcing materials due to limited availability (D6) (13.0%) and inaccurate demand forecasting (D1) (7.0%) were identified as the most significant risks, potentially leading to repeated verification processes, schedule delays, and cost overruns.

Overall, the Monte Carlo simulation and sensitivity analysis identified the five most critical risks affecting project supply chain performance. These findings provide the basis for developing targeted and practical risk mitigation strategies to reduce the impact of material supply chain uncertainties throughout the project lifecycle.

Table 4.The proposed mitigation measures.

No.	Dominant Risk	Proposed Mitigation Strategies
1	Material delivery delays due to freight forwarding services (S1)	a. Develop material delivery schedules with adequate time buffers, particularly for critical materials. b. Engage multiple freight forwarding providers to reduce dependence on a single logistics company. c. Periodically evaluate freight forwarder performance based on delivery timeliness and reliability. d. Maintain safety stock for long lead-time materials at the project site.
2	Procurement delays (P1)	a. Integrate procurement planning with the project schedule. b. Streamline procurement administration through standardized documentation and procedures. c. Establish alternative suppliers for critical materials. d. Conduct regular procurement progress monitoring by the procurement and project management teams.
3	Changes in demand during project execution (P4)	a. Review project design and material quantities before construction begins. b. Strengthen coordination among planning, construction, and procurement teams through regular coordination meetings. c. Implement a documented change management procedure.

No.	Dominant Risk	Proposed Mitigation Strategies
		d. Develop contingency plans to accommodate unexpected changes in material demand.
4	Difficulty in sourcing materials due to limited availability (D6)	a. Identify local and regional suppliers during the early project stage. b. Procure critical materials in advance (early procurement). c. Establish long-term partnerships with key suppliers to ensure material availability. d. Improve inventory management at the project warehouse.
5	Inaccurate demand forecasting (incorrect estimation of material quantities) (D1)	a. Improve quantity estimation using validated design data. b. Involve field personnel in material planning to reflect actual site conditions. c. Implement a material tracking system to monitor material requirements and consumption. d. Periodically review and update the material requirement plan throughout project execution.

The findings indicate that material supply chain risks are not confined to a single project phase but may arise throughout the project lifecycle, from planning to construction. Therefore, risk management should be implemented as a continuous and integrated process. The proposed mitigation strategies for the dominant risks are expected to reduce supply chain uncertainty while improving project schedule, cost, and quality performance in the Miu River and Tuva River Dam Consolidation Project.

Furthermore, the results highlight the importance of systematic risk assessment procedures within project management. The consistency between the Monte Carlo simulation results and the project's internal risk assessment demonstrates that the company's risk management practices provide a reliable basis for identifying and prioritizing critical risks. This alignment enhances the project's ability to anticipate uncertainties and supports more effective decision-making throughout project execution.

V. CONCLUSION

This study identified 33 material supply chain risks in the Miu River and Tuva River Dam Consolidation Project, classified into four dimensions: Demand, Process, Supply, and Control. The Monte Carlo sensitivity analysis revealed that the most influential risks were material delivery delays due to freight forwarding services (17.3%), procurement delays (14.5%), changes in demand during project execution (13.6%), difficulty in sourcing materials due to limited availability (13.0%), and inaccurate demand forecasting (7.0%).

The Monte Carlo simulation produced an overall Risk Index of 66.56%, indicating a relatively high level of material supply chain risk. To reduce these dominant risks, project managers should implement proactive procurement planning, conduct early procurement of critical materials, diversify logistics and supplier sources, maintain adequate inventory, and strengthen coordination among planning, procurement, and construction teams. These measures can improve supply chain reliability and enhance project schedule, cost, and quality performance.

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