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A Hybrid Failure Mode and Effects Analysis–Decision Tree Framework for Integrated Occupational Health and Safety Risk Assessment: A Case in Military Building Construction

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Abstract

Occupational health and safety in military construction projects face unique challenges due to security restrictions that complicate safety oversight and limit emergency response capabilities. While Failure Mode and Effects Analysis (FMEA) effectively identifies construction risks, it lacks structured decision-making for selecting optimal mitigation strategies. Existing frameworks focus on risk identification but provide limited guidance for cost-effective mitigation under resource and security constraints. This study develops the first integrated FMEA-Decision Tree framework specifically adapted for military construction environments, demonstrated through the Military Command Building A project. Six experienced stakeholders evaluated 28 construction activities, identifying six dominant risks with Risk Priority Number (RPN) values exceeding 150. The integrated methodology achieved significant RPN reductions ranging from 53.58 to 80.83 points, transitioning all critical risks from "Very High" to "High" categories. External validation through Hazard Identification, Risk Assessment, and Determining Control (HIRADC) confirmed consistent hazard identification. This pioneering approach demonstrates considerable potential for improving safety management in high-security construction contexts.

INTRODUCTION

The construction industry differs significantly from other sectors, such as manufacturing, due to its inherent uniqueness. It is widely recognized that no two construction projects are identical, as each one involves distinct conditions and challenges throughout its implementation [1,2]. Construction safety management plays a pivotal role in every development project, not only as a regulatory requirement but also as a strategic investment in long-term project sustainability. This is particularly critical in high-risk environments, such as military construction, where the stakes involve not just worker safety but also operational continuity and national security [3]. In Indonesia, the implementation of Construction Safety Management Systems (CSMS) has been formally mandated through Government Regulation No. 14 of 2021 and Ministerial Regulation No. 10 of 2021, both of which emphasize the

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importance of workplace safety, health, and risk control through the 4S framework (Safety, Health, Security, and Sustainability) [4–6].

Despite these regulatory advancements, the construction sector remains among the most hazardous industries globally [7,8]. The National Institute for Occupational Safety and Health (NIOSH) consistently reports that the construction sector experiences the highest fatality rates, particularly from falls and structural failures [9]. National data from Indonesia's BPJS Ketenagakerjaan echoes these concerns, recording over 289,000 workplace accidents as of September 2023, with construction-related incidents accounting for a significant proportion [10]. These realities underscore the urgent need for proactive risk assessment and mitigation strategies tailored to the construction industry.

Given the complexity and inherent risks in multi-story building projects, risk analysis becomes crucial for managing uncertainty and reducing negative impacts, thereby increasing project success rates [11]. One proven effective method for identifying potential hazards and risks is Failure Mode and Effects Analysis (FMEA). This method has been successfully applied in analyzing risks across various construction project types, including dam construction, toll road projects, and multi-story buildings [12,13]. FMEA provides a systematic approach to risk identification by evaluating three key parameters: Severity, Occurrence, and Detection, enabling comprehensive risk prioritization [14].

Military construction projects present unique challenges due to their highly secure nature and confidentiality requirements. These projects operate under enhanced security protocols that, while maintaining stringent safety standards for design and procedures, create unique implementation challenges. The restricted access nature of military construction sites can limit external safety oversight and emergency response capabilities, potentially affecting consistent enforcement of safety practices such as proper Personal Protective Equipment (PPE) usage among workers [15,16]. This situation creates potential risks for workers, supervisors, and individuals around the project site.

FMEA is a systematic risk assessment methodology originally developed by the U.S. military in the 1940s for enhancing weapons system reliability [17]. Previous research has demonstrated FMEA's effectiveness in various construction contexts. In the context of modern military construction, FMEA has proven particularly effective in identifying potential failure modes within design and construction processes, evaluating the impact of failures on military security and operational capabilities, and developing mitigation strategies that specifically address the confidentiality and security requirements inherent to military facilities [18,19]. Ibrahim et al. [20] successfully applied FMEA to identify critical failure modes in bridge construction, while Zhang et al. [21] utilized the method for tunnel construction risk assessment. However, limited research has specifically addressed FMEA application in military construction projects, despite the method's military origins and relevance to high-security construction environments [22].

The Decision Tree method provides a structured approach to decision-making by evaluating different mitigation alternatives based on their expected outcomes and associated probabilities [23]. This method has been successfully integrated with FMEA in various industries to optimize risk mitigation strategies [24]. The combination of FMEA for risk identification and Decision Tree for mitigation selection provides a comprehensive risk management framework suitable for complex construction projects.

This study responds to that gap by proposing an integrated methodology that combines FMEA with Decision Tree analysis, providing not only risk identification and prioritization, but also a structured, data-informed approach for selecting the most appropriate mitigation strategies. While both FMEA and Decision Tree have been applied individually in construction risk contexts, their combined use within a military setting, particularly in Indonesia, remains underexplored. Accordingly, this research aims to conduct a preliminary assessment of occupational health and safety (OHS) risks in the construction of Military Command Building A in Central Kalimantan Province by integrating FMEA and Decision Tree analysis. Specifically, this study seeks to: (1) systematically identify and prioritize construction safety risks using FMEA methodology, (2) evaluate the effectiveness of Decision Tree analysis in selecting optimal risk mitigation strategies, (3) assess the potential reduction in risk levels through targeted safety interventions, and (4) explore the applicability of this integrated approach for similar military construction contexts. The study contributes to the limited body of knowledge on risk assessment methodologies in high-security construction environments while providing preliminary insights for improving safety performance in military infrastructure projects.

LITERATURE REVIEW

Failure Mode and Effects Analysis (FMEA) in Construction

FMEA has a distinguished history in military applications, having been developed by the U.S. military in the 1940s, with its procedures first documented in MIL-P-1629 in 1949, and subsequently revised as MIL-STD-1629A in 1980. Originally employed to enhance the reliability of weapons systems, this methodology was later adopted by NASA, the automotive industry, and various other sectors, demonstrating its versatility and effectiveness across different domains [17].

In the context of modern military construction, FMEA has proven particularly effective in identifying potential failure modes within design and construction processes, evaluating the impact of failures on military security and operational capabilities, and developing mitigation strategies that specifically address the confidentiality and security requirements inherent to military facilities [18,19]. This systematic approach enables comprehensive risk assessment while maintaining the stringent safety and security standards essential to military infrastructure development, making it an invaluable tool for managing the unique challenges associated with military construction projects [17,24].

The method evaluates potential failure modes by assessing three key parameters: Severity (consequence impact), Occurrence (likelihood of failure), and Detection (ability to identify failure before occurrence) [14]. In construction contexts, FMEA has proven effective for identifying and prioritizing safety risks across various project types.

Recent applications of FMEA in construction include dam construction risk assessment [12], toll road project safety analysis [26], and multi-story building construction [13]. The method's strength lies in its systematic approach to failure mode identification and quantitative risk prioritization through Risk Priority Number (RPN) calculation [27]. However, while FMEA excels at risk identification and prioritization, it provides limited guidance for selecting optimal mitigation strategies among multiple alternatives.

Decision Tree Analysis in Risk Management

Decision Tree analysis provides a structured approach to decision-making under uncertainty by evaluating different alternatives based on their expected outcomes and associated probabilities [23]. The method calculates Expected Monetary Value (EMV) for each decision alternative, enabling objective comparison and selection of optimal strategies [24]. In risk management contexts, Decision Tree analysis has been successfully applied to optimize resource allocation and mitigation strategy selection.

The integration of Decision Tree analysis with risk assessment methodologies addresses the limitation of traditional risk identification approaches by providing systematic frameworks for mitigation selection [28]. This combination enables both comprehensive risk mapping and evidence-based decision-making for risk treatment strategies.

Construction Risks in Military Projects

Military construction projects present unique risk profiles compared to conventional construction due to security restrictions, limited external oversight, and specialized operational requirements [15]. Common risks identified in military construction include fall risk [18,19], equipment-related incidents [29], and material handling accidents [29,30]. These risks are often amplified by restricted emergency response access and limitations on external safety inspections inherent to high-security construction environments.

Previous research has identified key risk categories in military construction projects including: (1) height-related risks from elevated work activities [16], (2) equipment operation risk in confined spaces [29], (3) material handling risks under security constraints [30], (4) environmental exposure risks during outdoor construction [31], and (5) ergonomic risk from specialized construction requirements [32]. These risk categories form the foundation for systematic risk assessment in military construction contexts.

Research Gap and Contribution

While FMEA and Decision Tree analysis have been applied individually in various construction and military contexts, their integrated application specifically for military construction risk management remains limited. Existing research primarily focuses on either risk identification (through FMEA) or decision optimization (through Decision Tree) but rarely combines both approaches in a unified framework. Furthermore, most existing studies address conventional construction projects, with limited attention to the unique challenges and constraints of military construction environments.

This study contributes to existing knowledge by: (1) developing an integrated FMEA-Decision Tree framework specifically adapted for military construction contexts, (2) demonstrating the practical application of this integrated approach in a real military construction project, (3) providing empirical evidence of the framework's effectiveness in reducing identified risks, and (4) establishing a foundation for broader application of integrated risk management methodologies in high-security construction environments.

METHODS

Research Design

This study employs a case study methodology with quantitative risk assessment, specifically designed to develop and validate an integrated FMEA-Decision Tree framework for military construction safety management. The approach combines systematic risk identification through FMEA with structured decision analysis through Decision Tree methodology, enabling both comprehensive risk mapping and evidence-based mitigation selection.

Research Location

The research was conducted at the Development and Arrangement of Infrastructure and Facilities of Korem 102/Panju Panjung, specifically on the Military Command Building A project in Central Kalimantan Province, as can be seen in Figure 1.

The building covers 1,836 m² consisting of 3 floors with an implementation period of 120 calendar days, executed under the Central Kalimantan Province Department of Public Works and Spatial Planning (DPUPR). Building A construction began in late 2023 and was carried out in phases. This three-story building is intended for Command assistants and other supporting staff, serving as a new strategic command center considering Central Kalimantan Province is the largest province in Indonesia with an area of approximately 15 million hectares.

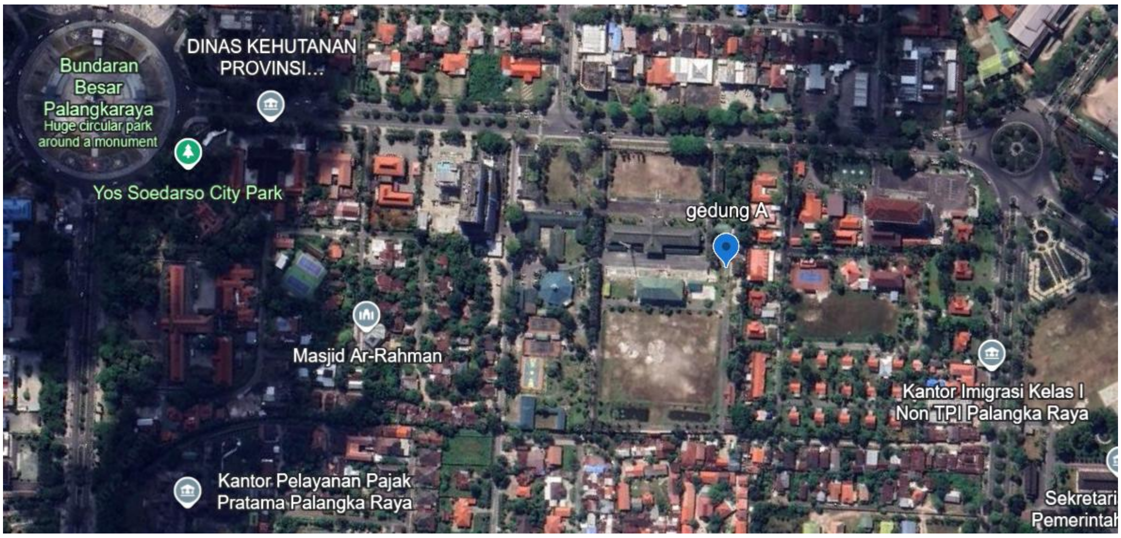

Figure 1. Location of Military Building Construction

Research Framework and Data Collection Methods

The research methodology follows a systematic framework that integrates FMEA analysis with Decision Tree methodology for comprehensive risk assessment and mitigation planning, as illustrated in Figure 2. This Figure shows the comprehensive research framework illustrating the sequential flow from research objectives through FMEA analysis to Decision Tree implementation. The framework demonstrates the integration of literature review, questionnaire development, risk assessment by multiple stakeholders (project owner, consultant, contractor), dominant risk identification, validation processes (both internal and external), and concludes with effectiveness evaluation and recommendations.

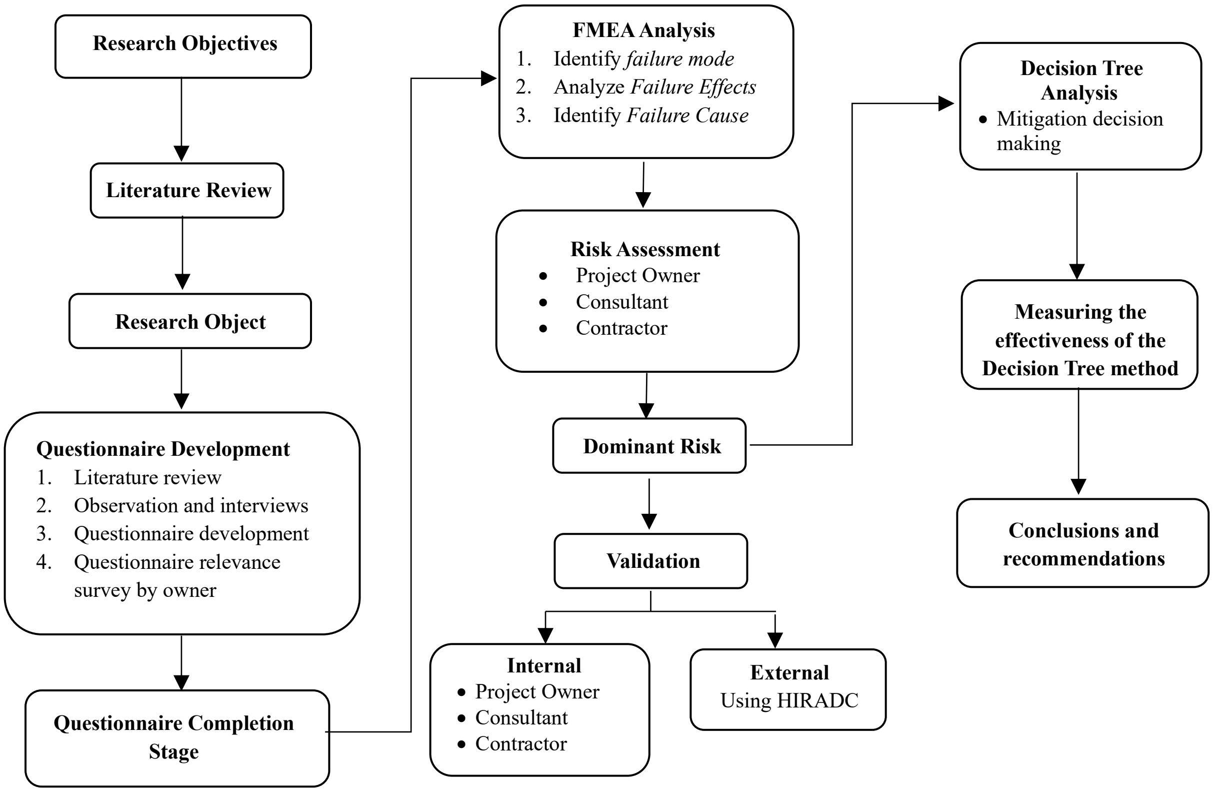

Figure 2. Research Framework

The framework encompasses several interconnected phases, beginning with research objective definition and progressing through literature review, research object identification, and questionnaire development.
The data collection process was structured through multiple complementary approaches:

1. **Literature Review**: Conducted to gather information, theories, concepts, findings, and gaps in previous research relevant to the research topic, forming the theoretical foundation for FMEA implementation.
2. **Documentation Study**: Conducted to collect information about Construction Safety Systems, including legislation, guidelines, and reports from the relevant project, providing regulatory context for risk assessment.
3. **Observation**: Conducted at the construction project site to directly observe how the Construction Safety Management System is implemented, ensuring practical relevance of identified risks.
4. **Interviews**: Conducted with research subjects to obtain information and potential risk relevant to Building A project, validating literature-based risk identification.
5. **Questionnaire Survey**: Data collection technique conducted by providing a set of written questions to respondents using a 1-10 Likert scale, enabling quantitative risk assessment across severity, occurrence, and detection parameters.

The framework demonstrates the systematic progression from initial research objectives through comprehensive risk analysis to practical mitigation recommendations, ensuring methodological rigor and practical applicability in military construction contexts.

FMEA Implementation

Failure Mode and Effects Analysis was implemented in five stages:

1. **Identification of Potential Failure Modes**: Aims to determine the impact of potential risks on system performance or project implementation processes.
2. **Analysis of Failure Effects**: Aims to evaluate consequences to determine priorities in handling more critical risks.
3. **Identification of Failure Causes**: The process of determining fundamental reasons (root causes) that cause a failure mode to occur.
4. **Risk Level Assessment**: Risk assessment in FMEA is conducted using three main parameters: Severity, Occurrence, and Detection on a 1-10 Likert scale referring to each parameter's criteria, as shown in Table 1.

Table 1. FMEA Assessment Criteria [32]

Rank	Effect of Severity	Likelihood of Occurrence	Likelihood of Detection
1	No effect	Very low	Almost certain
2	Disruption	Low	Very high
3	Disruption	Low	High
4	Loss of support function	Medium	Moderately high
5	Loss of support function	Medium	Medium
6	Loss of support function	Moderately high	Low
7	Loss/degradation of primary function	Moderately high	Very low
8	Loss/degradation of primary function	High	Affordable
9	Failure of potential accident and/or regulatory compliance	High	Very unaffordable
10	Failure of potential accident and/or regulatory compliance	Very high	Hardly affordable

The FMEA assessment criteria in Table 1 were adopted from automotive industry standards (AIAG-VDA) [33] and adapted for construction contexts based on their proven effectiveness in systematic risk evaluation. These criteria provide standardized scales for Severity (effect impact), Occurrence (likelihood), and Detection (identification capability) assessment, enabling consistent evaluation across different respondents and work activities. The 1-10 Likert scale offers sufficient granularity for meaningful risk differentiation while remaining practical for expert assessment in field conditions.

Risk categorization follows the criticality levels established in Table 2, which defines seven risk categories from Minor (RPN 0-1) to Extreme (RPN 500-1000) with corresponding action timeframes. Dominant risks in this study were established using the "Very High" threshold (RPN > 150), requiring immediate action within less than a day according to the established criteria [34].

Table 2. Risk Category Determination {34]

Color	Criticality Level	RPN Value	Recommendation
	Minor	0-1	Acceptable
	Very Low	1-5	Actions should be taken within less than a year
	Low	5-10	Actions should be completed within less than 3 months
	Medium	10-50	Actions should be completed within less than a month
	High	50-150	Actions should be completed within less than a week
	Very High	150-500	Actions should be completed within less than a day
	Extreme	500-1000	Actions must be taken quickly (immediately)

Mathematically, RPN values can be obtained through the following formula:
$RPN = S \times O \times D$ (1)
Where: S = Severity level; O = Occurrence frequency; D = Detection level

Decision Tree Analysis

The role of Decision Tree in decision-making serves as a tool to prioritize problems based on probability and impact identified in FMEA. Decision Tree analysis was conducted with the assistance of "QM For Windows" software with the following analysis stages:

1. **Decision Making with Decision Tree**: Mitigation action recommendations were obtained from research questionnaire forms, where after respondents completed FMEA assessments, there were columns for mitigation action suggestions for each work item. Decision Tree analysis involved RPN values from each respondent regarding suggested mitigation actions, enabling QM For Windows software to assist decision-making by selecting values/objectives in the form of minimal Expected Monetary Value (EMV) to reduce construction accident levels in Military Command Building A project.

Expected Monetary Value (EMV) calculation was performed using the following formula:

$$EMV = \Sigma(Pi \times Ri) \quad (1)$$

Where:

- Pi = Probability of risk occurrence after mitigation implementation
- Ri = Residual risk impact after mitigation
- EMV represents the expected risk reduction value for each mitigation strategy

Lower EMV values indicate more effective mitigation strategies. The Decision Tree analysis in QM for Windows software evaluated multiple mitigation alternatives for each dominant risk, selecting strategies that minimize expected residual risk while considering implementation feasibility and resource requirements.

2. **Decision Tree Method Effectiveness**: Measuring Decision Tree method effectiveness was conducted to determine the extent to which Decision Tree mitigation action decisions can reduce RPN values in dominant risk work items.

Research Respondents

The selection of six expert respondents aligns with established practices in FMEA applications for construction projects, where expert panels typically range from 5-10 participants to ensure manageable consensus-building while maintaining diverse perspectives. This sample size provides adequate representation across three critical stakeholder groups (owner, consultant, contractor) with two experts per group, ensuring balanced input from different organizational perspectives. All respondents possess substantial experience (10-21 years) and hold key positions directly involved in project safety management, meeting the expert qualification criteria recommended for FMEA studies. While larger samples might enhance statistical power, the focused expert panel approach prioritizes depth of expertise over sample size, consistent with FMEA methodology emphasis on informed professional judgment rather than statistical sampling.

Table 3. Characteristics of the Respondent

No.	Position in Project	Gender	Age (Years)	Education	Work Experience (Years)
1	Owner Representative	Male	52	Master's Degree	21
2	Site Engineer (Supervision Consultant)	Male	54	Bachelor's Degree	18
3	Owner Supervisor	Male	31	Bachelor's Degree	12
4	OHS Expert (Supervision Consultant)	Male	59	Bachelor's Degree	13
5	Site Manager (Contractor)	Male	46	Bachelor's Degree	10
6	Project Manager (Contractor)	Male	41	Bachelor's Degree	17.5

Table 3 presents the demographic and professional profiles of the six respondents involved in the study. All respondents are key project stakeholders directly engaged in the Military Command Building A construction project, representing the project owner, supervision consultant, and contractor. They include positions such as Owner Representative, Site Engineer, Owner Supervisor, OHS Expert, Site Manager, and Project Manager. Their backgrounds indicate a strong level of expertise, with ages ranging from 31 to 59 years and work experience between 10 and 21 years. The majority hold bachelor's degrees, while one holds a master's degree, reflecting a high level of competence in construction and occupational safety management. This distribution ensures diverse perspectives in assessing risks based on their experience and roles, enhancing the reliability and comprehensiveness of the FMEA analysis conducted in this research.

RESULTS AND DISCUSSION

FMEA Analysis Results

Identification of Potential Failure Modes, Failure Effects Analysis, and Failure Causes Identification

Potential failures specific to Building A were identified through site observation and stakeholder consultation. The identified failure causes were found to be consistent with findings from previous construction safety studies, confirming the validity of our empirical results. The potential failure modes in Table 4 were identified from relevant literature and verified through field observations to capture the most critical risks. These failures were then organized into work items following the common Work Breakdown Structure (WBS) of building projects, so that each risk could be linked directly to the activity where it most frequently occurs. Analysis of potential failure effects and identification of failure causes integrated three complementary approaches: (1) Literature review provided theoretical foundation and industry best practices for failure mode identification, (2) Direct site observation enabled validation of literature-based risks against actual project conditions and identification of site-specific risk, and (3) Structured interviews with project stakeholders captured experiential knowledge and context-specific risk factors unique to military construction environments. This triangulation approach ensured comprehensive risk identification while maintaining practical relevance to the specific project context. The results of potential failure modes, failure effects, and failure causes are presented in Table 4.

Table 4. FMEA Analysis Results

No.	Work items	Potential Failure Modes	Effects of Failure	Root Causes of Failure
A1	Preparation	Risk of being hit by heavy equipment	Hit by heavy equipment due to technical error when cleaning the work area	Lack of training and awareness of safety regulations, or lack of supervision and coordination between operators and workers in the work area [13,25]
A2		Visual and respiratory impairment	Exposed to vehicle fume dust	Dusty and polluted working conditions due to vehicle activity and dry or damaged road conditions, which increase airborne dust [29,30]
A3		Physical injury risk	Workers stabbed by sharp materials located at the project site	Improper and non-procedural arrangement and storage of materials, causing sharp materials to easily pose a risk of puncture [13,25,30]
B1	Soil and foundation	Fall risk	Workers fall/fall into excavation holes	Absence of warning signs or hazard markers around excavation sites, so workers and others are unaware of the danger of excavation pits [13,25,30]
B2		Health risk	Workers affected by dengue/infection due to waterlogged excavation holes (rainy season)	Inadequate management and prevention of water accumulation or absence of covers/safety barriers for excavation pits [13]
B3		Heavy equipment accidents	Heavy equipment crashes/falls on workers, equipment, and materials	Ineffective communication between heavy equipment operators and workers in the vicinity [13]
C1	Structure	Physical injury risk	Tears, bruises, or scratches due to reinforcing bars or formwork materials	Insufficient warning signs or barriers around areas containing sharp materials, causing workers to be unaware of the danger when near such materials [25,29,30,34]
C2		Fall from height risk	Workers fall during formwork installation at height (floors 2-4)	Absence or insufficient physical safety measures such as safety fences, safety nets, or barriers in formwork areas [13,25,30]
C3		Risk from machinery/heavy equipment	Concrete pumps and concrete mixers cause accidents if not used properly.	Insufficient coordination between heavy equipment operators and other workers at the site can lead to miscommunication, causing workers to enter hazardous zones without the operator's awareness [13,25,34]
C4		Risk from materials	material or cement splashes on workers/people in the area below the casting.	Installation of barriers, signs, or covers in the area below the concrete pour, allowing workers to freely move around under the hazardous zone [13,25,34]
D1	Wall	Risk from materials	Bricks falling on workers	Negligence or errors (human error) that can stem from worker fatigue [13,34]
D2		Risk from materials	Mortar splashes hitting the eyes	Can be caused by a lack of awareness among workers of the importance of using PPE (project helmets, masks, and goggles) to avoid such incidents [29,30,34]
E1	Frames, doors, windows, and accessories	Visual impairment	Exposure to dust from materials used in frame construction	Lack of awareness among workers of the importance of PPE (especially masks/eye protection) [31]
E2		Physical injury risk	Injuries caused by tools during installation	Workers not using appropriate personal protective equipment (PPE), such as thick gloves that can protect against sharp material punctures [30]
F1	Floor Covering	Physical injury risk	Workers hit by ceramic shards	Scattered ceramic debris or workers not paying attention to their work area [31]
F2		Risk from materials/equipment	Workers injured by cutting tools	Lack of understanding among workers about the safe use of cutting tools and proper work procedures, or failure to use

No.	Work items	Potential Failure Modes	Effects of Failure	Root Causes of Failure
				adequate personal protective equipment (PPE), such as specialized cut-resistant gloves/hand protection [29,30]
G1	Ceiling	Fall risk	Workers falling/slipping while lifting ceiling materials to high floors	Slippery, uneven, or unstable work surfaces that can cause slipping or loss of balance. Additionally, carelessness while working (lack of focus, rushing) [30,34]
G2		Health risk	Skin irritation/exposure to dust from finishing materials or chemicals during ceiling finishing	Direct exposure to finishing materials containing hazardous chemicals such as paint, thinner, solvents, and adhesives that can cause skin irritation [31]
H1	Mechanical and electrical	Fall risk	Installation work is often performed at heights, such as on ceilings or roofs	Undisciplined work attitudes, such as disregarding safety procedures, as well as unstable work surfaces (ladders/scaffolding) can increase the risk [30,34]
I1	Plumbing	Risk from materials	Workers may sustain injuries while handling pipes and are at risk of being struck by pipe installation equipment	Improper installation procedures, careless workers, and failure to use personal protective equipment (PPE) can increase the risk level [29,30,34]
I2		Fall Risk	Slipping due to spilled water/water puddles during work	The absence or insufficient use of anti-slip mats or work surface protectors can reduce the risk of slipping [29,30]
J1	Painting	Risk from Materials	Workers struck by paint can materials	Unorganized materials at the work site increase the risk of tripping, slipping, or being struck by materials, leading to physical injury [13]
K1	Facades	Physical Injury Risk	Physical injuries due to careless handling of glass materials (scratches/bruises)	Cramped and cluttered work areas that make it difficult for workers to move safely can cause work-related risks [29,30]
K2		Weather-related risks	Worker fatigue due to working outdoors in rainy or extremely hot weather	Direct exposure to extreme weather conditions such as intense sunlight/rain, as well as insufficient rest periods, can cause dehydration, heat stress, and physical fatigue [31]
K3		Risk from Materials	Lifting materials, falling materials can cause injuries to workers below and property damage	Failure to properly mobilize materials, which may be caused by operators, and insufficient supervision of the lower areas during material mobilization using an excavator [30]
L1	Interior	Ergonomic Risk	Muscle injuries/pain when lifting/moving furniture or other heavy materials	Lack of training in ergonomics and proper lifting techniques, as well as workers who are physically unfit or fatigued [32]
L2		Physical Injury Risk	Sharp objects such as glass and metal, or sharp edges of materials, can cause cuts	Sharp and dangerous materials are not properly secured, posing a potential risk of workplace accidents [29,30]
M1	Site Development	Heavy Equipment Accidents	During the construction of temporary roads and supporting infrastructure, workers are at high risk of being hit by heavy vehicles operating in the area	The absence of physical protection systems such as protective fences or restricted zones around heavy equipment, making it easy for workers or materials to be struck [28,35]
M2		Occupational Accidents	During excavation and backfilling, excavation that does not consider safe slopes can trigger landslides, which can potentially injure workers and damage surrounding infrastructure.	Heavy rain or extreme weather changes that are not accounted for can weaken slope stability. Additionally, the accumulation of heavy materials near the edge of the slope can increase the load and trigger landslides [36,37]

Risk Assessment

The comprehensive risk assessment conducted across 28 distinct work activities in the Military Command Building A project reveals the distribution of occupational health and safety risks throughout different construction phases are presented in Table 5. Through systematic evaluation by six experienced professionals representing contractors, owners, and consultants, the analysis generated RPN values ranging from 50.95 to 179.83, with an overall mean of 115.89.

Table 5. Risk Assessment Results

No.	Work Items	Risk Assessment (RPN Value)			Average	Criticality Level
		Contractor	Owner	Consultant		
A1	Preparation	34.37	60.75	57.75	50.95	High
A2		27.00	99.00	121.00	82.33	High
A3		148.50	135.00	128.00	137.16	High
B1	Soil and foundation	126.00	121.87	108.00	118.62	High
B2		61.250	50.62	50.62	54.16	High
B3		112.50	134.75	117.00	121.41	High
C1	Structure	148.50	115.50	108.00	124.00	High
C2		156.00	180.00	196.00	177.33	Very High
C3		63.00	45.50	46.87	51.79	High
C4		173.25	169.00	154.00	165.41	Very High
D1	Wall	66.00	74.25	123.75	88.00	High
D2		62.50	108.00	100.00	90.16	High
E1	Frames, doors, windows, and	175.50	173.25	175.50	174.75	Very High
E2	accessories	137.50	99.00	135.00	123.83	High
F1	Floor Covering	135.00	136.12	146.25	139.12	High
F2		94.50	143.00	121.00	119.50	High
G1	Ceiling	108.00	141.75	148.50	132.75	High
G2		112.50	136.12	135.00	127.87	High
H1	Mechanical and electrical	141.75	96.00	132.00	123.25	High
I1	Plumbing	105.00	70.87	50.00	75.29	High
I2		178.75	182.00	178.75	179.83	Very High
J1	Painting	70.87	67.37	105.00	81.08	High
K1	Facades	137.50	144.00	99.00	126.83	High
K2		165.00	151.25	166.37	160.87	Very High
K3		101.25	86.62	90.00	92.62	High
L1	Interior	180.00	175.50	160.87	172.12	Very High
L2		137.50	135.00	120.00	130.83	High
M1	Site Development	94.50	107.25	86.62	96.12	High
M2		105.00	68.25	70.00	81.08	High

The assessment results demonstrate that six activities fall within the "Very High" risk category (RPN > 150), representing 21.4% of all evaluated work items. These critical activities include Plumbing I2 (179.83), Structure C2 (177.33), Frames E1 (174.75), Interior L1 (172.12), Structure C4 (165.41), and Facades K2 (160.87). The remaining 22 activities (78.6%) were categorized as "High" risk (RPN 50-150), while notably, no activities registered in the low-risk category (RPN < 50).

Dominant Risk Identification

Dominant risks were determined based on RPN values above 150, which fall within the Very High-risk category requiring immediate action within less than a day (Table 2). Analysis revealed six dominant risks across Building A's construction activities. The highest risk was identified in Plumbing (I2), where workers face fall hazards due to slipping from water spills during work, with an RPN of 179.83. Close behind were Structure-related risks, including falls from height during formwork installation at floors 2-3 (C2, RPN: 177.33) and material hazards from cement splashes on workers below casting areas (C4, RPN: 165.41). Additional dominant risks include visual impairment from dust exposure during frame construction (E1, RPN: 174.50), physical injuries from sharp objects such as glass and metal in interior work (L1, RPN: 172.12), and weather-related impacts causing worker fatigue during outdoor facade work (K2, RPN: 160.87)

External Validation

External validation was conducted through comparison with Hazard Identification, Risk Assessment, and Determining Control (HIRADC) methodology previously applied at the same construction site. The HIRADC approach systematically identifies potential risks through workplace inspection and activity analysis, evaluates risks using likelihood and consequence matrices (1-5 scale), calculates risk levels through multiplication of these parameters, and determines appropriate control measures following risk hierarchy principles. The HIRADC assessment, conducted by the same project team during earlier project phases, provided an independent baseline for validation. Risk levels from HIRADC (scale 1-25) were converted to comparable categories (Low, Medium, High, Very High) for alignment with FMEA risk classifications, as presented in Table 6.

Table 6. External Validation Comparison of FMEA and HIRADC

FMEA		**HIRADC**	
Overall Structural Work		Floor plate work	
Risk Identification	RPN	Risk Identification	Risk Level
Danger of falling from heights: workers fell while installing formwork at heights (floors 2-4)	177.33	Risk of falling: workers are on the second floor, so there is a risk of falling from a height.	10
Risk Category	Very High	Risk Category	High
Overall Structural Work		Floor plate work	
Risk Identification	RPN	Risk Identification	Risk Level
Danger from Materials: material or cement splashes hitting workers/people in the area below the casting site.	165.41	Falling or spilled material: Casting involves liquid concrete that could potentially fall from a height or spill. This could cause injury to workers below the casting site	8.4
Risk Category	Very High	Risk Category	High

The comparative analysis presented in Table 6 reveals encouraging convergent validity in hazard identification, with both FMEA and HIRADC methods consistently recognizing fall-from-height dangers and material spillage risks as the dominant safety concerns in structural work activities. Specifically, both approaches identified workers falling during formwork installation at elevated floors and cement splash hazards affecting personnel below casting areas as critical safety issues requiring immediate attention. However, significant methodological differences emerged in risk quantification and categorization schemes, with FMEA generating RPN values of 177.33 and 165.41 respectively, while HIRADC produced risk levels of 10.0 and 8.4 on a different scale range, making direct quantitative comparison challenging without appropriate scale conversion protocols.

Decision Tree Analysis Results

Decision Making Process

Table 7. Decision Tree Analysis Results Following Hierarchy of Risk Control

Work Items	**Control Level**	**Recommended Mitigation Actions**	**RPN**	**EMV**
Structure (C2)	Engineering Control + Administrative	Install permanent safety barriers and guardrails; Implement mandatory safety briefings and work permits for height work	123.75	150.54
Frames (E1)	Engineering Control + PPE	Install dust extraction systems at work areas; Provide respiratory protection equipment (N95 masks, safety goggles)	120.00	147.38
Interior (L1)	Substitution + PPE	Replace sharp-edged materials with rounded alternatives where possible; Mandate cut-resistant gloves and safety footwear	110.00	141.06
Structure (C4)	Engineering Control	Install protective screens and containment systems around concrete pour areas; Establish exclusion zones below work areas	99.25	132.33
Plumbing (I2)	Engineering Control + PPE	Install permanent scaffolding with anti-slip surfaces; Provide fall arrest harnesses and safety helmets	99.00	139.42
Facades (K2)	Administrative Control	Implement weather monitoring systems; Establish worker rotation schedules during extreme weather; Provide climate-controlled rest areas	98.00	129.44

The Decision Tree analysis provides a systematic approach to prioritizing and evaluating mitigation strategies for identified construction risks. Table 7 demonstrates how the Decision Tree method assigns Expected Monetary Values

(EMV) to different mitigation actions, enabling objective comparison of alternatives. Risk mitigation strategies in this study follow the Hierarchy of Risk Control, prioritizing elimination of hazards where feasible, followed by substitution with safer alternatives, engineering controls through physical safeguards, administrative controls including training and procedures, and personal protective equipment (PPE) as the final protective barrier. This approach emphasizes higher-order controls over PPE alone, consistent with established occupational safety principles.

Decision Tree Method Effectiveness

The effectiveness of the Decision Tree methodology becomes particularly evident in Table 8, which tracks the quantitative impact of implemented mitigation measures.

Table 8. Decision Tree Effectiveness Analysis

Work Items	Recommended Actions	Previous RPN	Current RPN	Difference
Plumbing (I2)	Strong scaffolding with safety equipment	179.83	99.00	80.83
Structure (C2)	Warning signs and safety briefings	177.33	123.75	53.58
Structure (C4)	Clear boundary zones during casting	165.41	99.25	66.16
Facades (K2)	Weather protection and worker rotation	160.87	98.00	62.87
Interior (L1)	Protective equipment requirements	172.12	110.00	62.12
Frames (E1)	Dust protection equipment	174.75	120.00	54.75

The Current RPN values in Table 8 represent post-mitigation risk levels obtained through expert panel re-assessment. Following the same FMEA protocol, the panel re-evaluated Severity, Occurrence, and Detection parameters for each work item, assuming full implementation of recommended actions. Typically, Severity remained constant (representing inherent consequence), while Occurrence decreased (due to preventive controls) and Detection improved (through enhanced monitoring). For instance, implementing 'strong scaffolding with safety equipment' for Plumbing (I2) reduced RPN from 179.83 to 99.00, primarily by lowering fall occurrence probability and improving hazard detectability, while maintaining the same severity level for potential fall consequences.

Discussion

Risk Assessment in Military Construction Context

The identification of dominant risks in military construction projects reveals unique challenges compared to conventional construction. The highest risk identified (Plumbing I2, RPN: 179.83) relates to slip hazards from water spills, which is particularly critical in military facilities where emergency response may be limited due to security protocols [38,39]. Similarly, fall from height risks (Structure C2, RPN: 177.33) require enhanced safety measures given the restricted access for emergency services in military zones [41].

The prevalence of dust-related visual impairment (Frames E1, RPN: 174.75) in military construction reflects the need for specialized PPE that does not compromise security protocols while ensuring worker safety [42]. This finding aligns with previous research indicating that confined construction environments require adapted safety measures [43].

Stakeholder Risk Perception Analysis

The assessment revealed significant variations in risk perception among stakeholder groups, with differences exceeding 40 RPN points in several activities. Contractors consistently provided more conservative assessments, possibly reflecting their direct operational experience and responsibility for worker safety implementation. Consultants demonstrated higher risk sensitivity, potentially influenced by their oversight role and liability considerations. Owner representatives maintained moderate positions, balancing operational requirements with safety considerations.

These perception differences highlight the importance of multi-stakeholder input in risk assessment. Items D1 (Wall work), I1 (Plumbing), and K1 (Facades) showed the greatest assessment disparities (57.75, 55.0, and 45.0 RPN points respectively), suggesting these activities require additional clarification of risk factors and standardized assessment protocols. The consensus achieved in items E1, I2, and C2 (variations < 5 RPN points) validates the assessment methodology's reliability for clearly defined risk.

Study Limitations

This study acknowledges several critical limitations affecting interpretation and generalizability. The single-case study design limits statistical generalizability, while the expert panel size (n=6), though adequate for FMEA applications, restricts statistical power for broader inference. The external validation covered only 7% of identified risks (2 of 28 items) using different assessment scales, limiting comprehensive validation of the integrated methodology.

Methodological limitations include the subjective nature of FMEA scoring without formal inter-rater reliability assessment, cross-sectional design preventing longitudinal effectiveness evaluation, and focus on risk reduction without comprehensive cost-benefit analysis. The integration benefits of combining FMEA with Decision Tree analysis were not systematically compared against individual method applications.

Contextual limitations significantly affect transferability beyond the Indonesian military construction context. The three-story building scope may not represent complex military infrastructure requirements, while tropical climate conditions and local regulatory frameworks limit applicability to different geographical and organizational contexts. The framework's scalability to larger projects and compatibility with international military construction standards remains unestablished.

Future research should address these limitations through multi-site validation studies, longitudinal effectiveness assessment, formal reliability testing, and cross-cultural validation to establish broader applicability and develop more comprehensive risk management frameworks for diverse military construction contexts.

CONCLUSIONS

This research successfully implemented and evaluated an integrated FMEA and Decision Tree methodology for occupational health and safety risk assessment in a military construction project. The study identified 28 distinct work activities and revealed six dominant safety risks with RPN scores above 150, categorized as "Very High" risk: Plumbing I2 (179.83), Structure C2 (177.33), Frames E1 (174.75), Interior L1 (172.12), Structure C4 (165.41), and Facades K2 (160.87). These risks were primarily associated with fall risk, material handling issues, and environmental exposure challenges specific to military construction environments.

The Decision Tree approach demonstrated its effectiveness in supporting mitigation strategy selection, achieving RPN reductions ranging from 53.58 to 80.83 points across all identified dominant risks. All critical risks were successfully reduced from the "Very High" risk category (RPN > 150) to the "High" category (RPN < 150), representing substantial safety improvements. Limited external validation through comparison with the HIRADC methodology showed consistent hazard identification for structural work activities, supporting the reliability of the FMEA approach in this specific context.

This study provides a preliminary foundation for risk management in military construction projects and demonstrates the potential value of integrating quantitative risk assessment methodologies in high-security construction environments. The specific mitigation measures identified—including enhanced scaffolding systems, improved personal protective equipment protocols, weather protection strategies, and worker rotation programs—offer practical starting points for improving safety in similar projects. Future research should focus on multi-project validation, cross-cultural applicability assessment, and integration with existing military construction standards to develop more comprehensive and validated risk management frameworks for military infrastructure development.

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