

Adaptive Risk Metric Framework for Tower Crane Safety in High-Rise Construction Projects

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Abstract: Tower cranes are indispensable to high-rise construction, enabling the safe and efficient lifting of heavy materials to considerable heights. However, their operations are fraught with inherent dangers, making tower crane safety a critical area of concern. Despite technological advancements and evolving safety regulations, crane operation hazards continue to contribute to severe injuries and fatalities on construction sites. The study emphasizes the identification and examination of safety risks involved in the utilization of tower cranes within tall building construction. A comprehensive research approach was adopted, involving a systematic literature review and field-based data collection through structured surveys. These surveys were designed using a risk assessment checklist and evaluated through a tailored Severity-Likelihood-Detection (SLD) matrix, allowing for a detailed examination of key risk factors. The analysis revealed that proactive strategies such as real-time weather alerts and continuous visual monitoring can significantly reduce the likelihood of crane-related accidents. By prioritizing the identified risks, this study proposes practical, evidence-based measures to enhance safety standards in high-rise projects. The findings aim to guide stakeholders in implementing more effective risk mitigation strategies for safer crane operations.

Keywords: Tower crane safety, high-rise construction risks, crane operations hazards, risk assessment checklist, and SLD matrix

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1. Introduction

1.1. General Overview

Tower cranes are essential for high-rise construction, enabling efficient movement of heavy materials to great heights, particularly in space-constrained urban areas (Tam and Fung, 2011; Zhou et al., 2018). Ismail and Muhamad (2018) and Wu et al. (2022) observed that despite their efficiency, these cranes pose significant risks due to operating at extreme heights under high tension, with hazards including equipment failures, adverse weather, and human errors. Crane-related accidents remain prevalent despite advancements in technology and stricter safety regulations, causing severe injuries, fatalities, and financial losses (Lingard et al., 2021; Swuste, 2013). Key risk factors include structural instability, poor maintenance, and human oversight, highlighting the need for robust risk assessments and safety protocols (Raviv et al., 2017; Shin, 2015). Given that crane incidents account for a substantial portion of construction-related fatalities, stringent safety measures are considered critical (Chen et al., 2022; Sadeghi and Zhang, 2024). This study examines crane safety by analyzing accidents, identifying risks, and evaluating current practices. It seeks to bridge the gap between theoretical safety standards and their practical application, thereby enhancing safety in construction practices (Ali et al., 2024; Zhou et al., 2018). Shin (2015) and Tam and Fung (2011) highlighted that, approximately 80% of crane accidents are linked to human error, maintenance lapses, or environmental factors, a statistic that underscores the importance of improved safety practices.

1.2. Objectives and Scope

The objectives of this study are to: (1) identify and analyze major hazards in tower crane operations, and (2) propose risk mitigation strategies to enhance safety.

This study focuses on assessing risks such as mechanical failures, operator errors, and environmental factors using a semi-quantitative approach to prioritize safety interventions (Hu et al., 2023; Lingard et al., 2021). As demonstrated by Raviv et al. (2017) and Sadeghi and Zhang (2024), tools like the Fishbone diagram and RASM (Risk Assessment and Safety Management) matrix can be used to visualize and quantify these risks, aiding stakeholders in addressing critical areas promptly. This research provides safety managers, supervisors, and policymakers with a structured framework to improve safety practices and ensure regulatory compliance in high-risk construction environments (Ali et al., 2024; Sanni-Anibire et al., 2020).

1.3. Needs of the Present Study

Tower crane operations in high-rise construction pose significant risks due to their height, weight, and operational complexity. While crucial for material handling, accidents involving these cranes can lead to severe injuries, fatalities, and substantial financial losses, underscoring the need for a structured risk assessment approach (Hu et al., 2023; Lingard et al., 2021). Raviv et al., (2017) and Zhou et al. (2018) emphasized that the inadequate safety measures and ineffective risk models contribute to frequent crane accidents, often caused by operator errors, mechanical failures, poor visibility, and ground instability. Existing risk assessment techniques frequently fail to address the unique challenges of tower crane operations. A combined quantitative and qualitative risk assessment framework, incorporating factors like severity, likelihood, and detection, enables safety professionals to prioritize hazards and allocate resources effectively. This approach is essential for fostering a stronger safety culture in fast-paced construction environments (Sanni-Anibire et al., 2020; Ali et al., 2024). As noted by Chen et al. (2022) and Sadeghi and Zhang (2024), this study also addresses a gap in research by focusing on the specific challenges of high-rise construction, particularly in rapidly urbanizing regions.

1.4. Causes of Accidents

Lingard et al. (2021) highlighted that tower crane accidents often result from mechanical failures, human error, environmental factors, and inadequate maintenance. Improper assembly, unstable foundations, and incorrect installation practices can cause cranes to tip or collapse, especially under load. Human errors, including insufficient operator training and communication lapses, are also significant contributors. Neitzel et al. (2001) explained that misjudging load balance or failing to interpret hand signals can lead to accidents, highlighting that it's essential to implement more comprehensive training sessions and effective communication protocols to improve safety overall. Mechanical failures, often due to poor maintenance of key crane components, also plays a role in crane accidents. Over time, wear on parts like bolts and cables can cause failures if not addressed in a timely manner (Lingard et al., 2021; Tam and Fung, 2011). The process of installation and dismantling also present risks requiring strict adherence to these protocols (Shin, 2015). Environmental conditions, particularly high winds, can severely impact crane stability, making real-time weather monitoring vital for ensuring safe operations (Hu et al., 2023; Sadeghi and Zhang, 2024). Inadequate risk assessments and safety planning exacerbate these issues, highlighting the importance of comprehensive risk models to proactively identify safety hazards (Raviv et al., 2017; Sanni-anibire et al., 2020). Finally, Ali et al. (2024) and Wu et al. (2022) concluded that technological innovations, such as blockchain-enabled safety monitoring systems, can reduce accidents by providing real-time data and enabling swift responses to emerging risks.

1.5. Construction Safety Performance

Integrating safety considerations from the design stage can significantly reduce these risks, with studies indicating that design issues contribute to 42% of construction accidents (Gambatese et al., 2008). Structured safety frameworks that combine leadership engagement and standardized protocols are essential for managing risks in high-rise construction (Raheem and Issa, 2016). Safety performance can be evaluated using metrics such as accident rates and adherence to protocols, with proactive approaches emphasizing hazard identification and targeted training practices (Lingard et al., 2021; Tam and Fung, 2011). Equipment reliability and regular maintenance are also crucial for minimizing operational risks (Lingard et al., 2021; Swuste, 2013). Zhou et al. (2018) and Wu et al., (2022) emphasized that human factors, including inadequate training and miscommunication play a role in accidents, though technologies such as blockchain show promise in enhancing safety through real-time monitoring. Effective risk assessments, particularly those that incorporate safety early in project planning, have been shown to reduce accident rates (Ismail and Muhamad, 2018; Sanni-Anibire et al., 2020). Hu et al., (2023) found that environmental factors, such as weather conditions, must be integrated into safety planning, while emerging technologies like automated systems offer innovative solutions for mitigating human error (Ali et al., 2024; Sadeghi and Zhang, 2024).

2. Methodology

2.1. Literature Review

The literature review highlights that tower crane accidents are often the result of interconnected factors, including human error, environmental conditions, and equipment malfunctions. Shin (2015) and Tam and Fung (2011) identified specific risks, such as improper crane assembly or disassembly, insufficient operator training, and the spatial limitations in urban construction zones contribute to higher accident rates. A systematic review of 17 research papers was conducted, and based on their findings, the most frequently cited causes of tower crane accidents were identified and finalized for further analysis. These causes include collapses, falls, struck-by incidents, electrical hazards, mechanical failures, operator errors, poor visibility, ground failure, and inadequate maintenance. Lingard et al. (2021) suggested that such an approach enables researchers to identify recurring patterns and underlying causes, guiding targeted improvements in crane safety practices. This methodology informed the current study's research design, which combines literature review, expert interviews, and site observations to map causes using the Ishikawa diagram systematically.

2.2. Fishbone Diagram

From Table 1, the primary causes for accidents have been identified. To facilitate a more detailed study, an Ishikawa diagram (also known as the Fishbone diagram) was prepared to identify the various sub-causes of tower crane accidents. As shown in Fig.1, this diagram serves as a valuable tool for identifying and categorizing the root causes of such accidents in high-rise construction. It organizes potential causes into key categories, such as human factors, equipment and machinery, methods, and materials, each branching into specific sub-causes.

Table 1. Literature review summary

Literature	Types of tower crane accidents								
	Collapses	Falls	Struck-by incidents	Electrical hazards	Mechanical failures	Operator errors	Poor visibility	Ground failure	Inadequate maintenance
Tam and Fung (2011)	✓					✓			
Shin (2015)	✓								
Lingard et al. (2021)	✓			✓		✓		✓	
Ismail and Muhamad (2018)	✓	✓	✓			✓	✓		
Swuste (2013)	✓	✓			✓				✓
Hu et al. (2023)	✓	✓		✓			✓	✓	
Zhou et al. (2018)	✓								✓
Raviv et al. (2017)				✓	✓	✓			✓
Sanni-Anibire et al. (2020)	✓	✓	✓	✓		✓	✓		
Chen et al. (2022)	✓	✓				✓			
Wu et al. (2022)		✓		✓	✓	✓			
Ali et al. (2024)	✓					✓	✓		
Sadeghi and Zhang (2024)	✓	✓	✓	✓		✓			✓

For example, human factors may include operator error or inefficient training, while equipment-related issues might involve mechanical failure or inadequate maintenance. Unsafe lifting procedures and overloading are also common contributing factors. A structured research methodology was followed to construct this diagram, incorporating a literature review of past crane accidents, expert interviews with site personnel, and on-site observations. Ismail and Muhamad (2018) and Lingard et al. (2021) suggested that the resulting diagram offers a clear, organized view of complex, interrelated causes, supporting the development of more effective accident prevention strategies.

2.3. Questionnaire Formulation, Execution, and Interpretation

The expert consultation process for this study employed a structured approach to gather diverse, field-relevant insights on tower crane risks. A total of 100 industry professionals participated, representing a wide demographic profile that included site engineers, safety officers, project managers, crane operators, and maintenance supervisors. Participants were selected from ten large-scale high-rise construction projects across various urban regions in India, ensuring a broad representation of perspectives. All experts possessed a minimum of five years experience in crane-related operations, and many held certifications in construction safety or equipment handling. In addition to expert surveys, a systematic document review was conducted to identify existing risk factors and inform the development of survey items. Sources reviewed included national and international crane operation safety guidelines (e.g., OSHA, ISO standards), previous accident investigation reports, and peer-reviewed journal articles on construction safety.

The interviews followed a semi-structured format, combining fixed-response survey elements with open-ended questions to allow for both quantifiable scoring and in-depth qualitative feedback. Experts were first asked to rate the severity, likelihood, and detectability of common crane-related hazards on a standardized 1-5 scale, forming the basis for the RPN calculations. Following the scoring phase, open-ended sections prompted participants to elaborate on specific causes they encountered on-site, effective mitigation measures, and suggestions for improving existing safety practices. As Swuste (2013) and Ismail and Muhamad (2018) noted, this combination of structured scoring and narrative input ensured a balanced, data-rich foundation for the risk assessment and helped validate the findings against real-world conditions. The 2 methods are elaborated as follows:

2.3.1. Risk Assessment Scoring Methodology (RASM)

RASM method is used to evaluate risks by assigning numerical scores to the severity, likelihood, of potential hazards as detailed in tables 2,3, and 4. Expert feedback is collected through surveys and converted into numerical scores, which are then analyzed using comparison matrices. Hazards are compared pairwise based on their severity, and scores are normalized on a 1-5 scale, taking into account their occurrence frequency. This process enables clear prioritization of risks, facilitating informed decision-making for effective risk management (Thompson et al., 2022).

2.3.2. Rank-Weighted Assessment Survey

The accident causes identified in this study were ranked based on feedback from 100 professionals working across 10 prominent construction sites in India. Each respondent was asked to score the perceived impact of each cause/risk on on-site safety, using a scale from 1 to 5, where 1 represents no impact and 5 represents a critical impact. This ranking helps in prioritizing the most significant accident causes and forms the basis for a comprehensive risk assessment approach. The survey results are presented in Table 5, which outlines the ranked causes and their associated risk levels providing a foundation for further analysis.

2.4. Development of Safety Risk Analysis Framework

The risk assessment approach for tower crane operations involves multiple stages, illustrated in Table 5, from hazard identification to calculating an Adjusted Risk Rating. Tam and Fung (2011) and Lingard et al. (2021) highlighted that this method synthesizes expert insights, empirical data, and structured formulas to prioritize risks effectively, allowing for targeted mitigation strategies.

2.4.1. Set Safety Goals

The first step involves establishing clear safety objectives for crane operations, focusing on preventing accidents and ensuring worker safety during all crane activities.

2.4.2. Map Hazards Using Cause and Effect Analysis

The second step utilizes a cause-and-effect (Ishikawa) diagram to systematically identify hazards. Zhou et al. (2018) and Ismail and Muhamad (2018) indicated that this analysis involves reviewing past accident data and literature to pinpoint common risks like crane collapses, falls, mechanical failures, and operator errors. The results are then visualized in a fishbone diagram, which categorizes hazards into distinct branches, helping to organize and analyze the root causes of accidents.

2.4.3. Estimate Risk Score Using RASM

In this step, each identified hazard is evaluated using the Risk Assessment Scoring Methodology (RASM). The risk score is calculated by multiplying three factors: severity, likelihood, and detection. These factors are rated on a scale from 1 to 5. The severity represents the potential impact of the hazard, the likelihood assesses the probability of the hazard occurring, and the detection evaluates how easily the hazard can be identified in advance using Eq. (1).

$$\text{Risk Score} = \text{Severity} \times \text{Likelihood} \times \text{Detection} \quad (1)$$

2.4.4. Prioritize Hazard Level

Hazard criticality is calculated by multiplying severity and likelihood scores using Eq. (2):

$$\text{Hazard Criticality} = \text{Severity} \times \text{Likelihood} \quad (2)$$

This calculation helps prioritize hazards based on their potential for immediate impact, without considering detection. For example, a hazard with a severity of 4 and likelihood of 3 would have a criticality score of 12, indicating a high priority for mitigation (Swuste, 2013).

2.4.5. Ascertain Risk Priority Number (RPN)

Industry-specific surveys are conducted to refine risk assessments, collecting input from construction safety professionals. These professionals assign severity, likelihood, and detection ratings to hazards based on real-world experience. The RPN is then calculated by using Eq. (3):

$$\text{RPN} = \text{Severity} \times \text{Likelihood} \times \text{Detection} \quad (3)$$

This empirical approach ensures that the risk assessment reflects practical insights, enhancing its relevance for field application (Chen et al., 2022; Wu et al., 2022).

2.4.6. Adjusted RPN Calculation

The RPN values are adjusted to allow for more nuanced risk differentiation. The adjustment involves taking the reciprocal of each raw RPN score, yielding a refined measure that factors in frequency and severity without distorting relative risk levels using Eq. (4):

$$\text{Adjusted RPN} = (\text{RPN} / \text{maximum possible RPN}) \times 100 \quad (4)$$

Ali et al. (2024) and Sadeghi and Zhang (2024) explained that the Adjusted RPN values help distinguish high-priority hazards clearly, as noted in methodologies applied across construction sites for improving safety performance.

2.4.7. Determine Risk Levels

The Risk Rating is derived from the adjusted RPN to categorize the hazards into tiers, with higher ratings indicating greater urgency, such as 5 (High risk) and 1 (low risk). This standardizes risk levels across multiple hazards, making it easier to implement targeted risk control measures (Hu et al., 2023).

2.4.8. Adjusted Risk Ratings

The final Adjusted Risk Rating, which scales the risk based on a percentage, is calculated using the formula in Eq. (5):

$$\text{Adjusted Risk Rating} = \text{Adjusted RPN} \times \text{Risk Rating} / 4\% \quad (5)$$

This formula provides a percentage-based risk value, allowing for prioritization and resource allocation based on risk levels. The 4% scaling factor ensures that ratings are standardized across different contexts, aligning with best practices in risk management (Raviv et al., 2017; Sadeghi and Zhang, 2024).

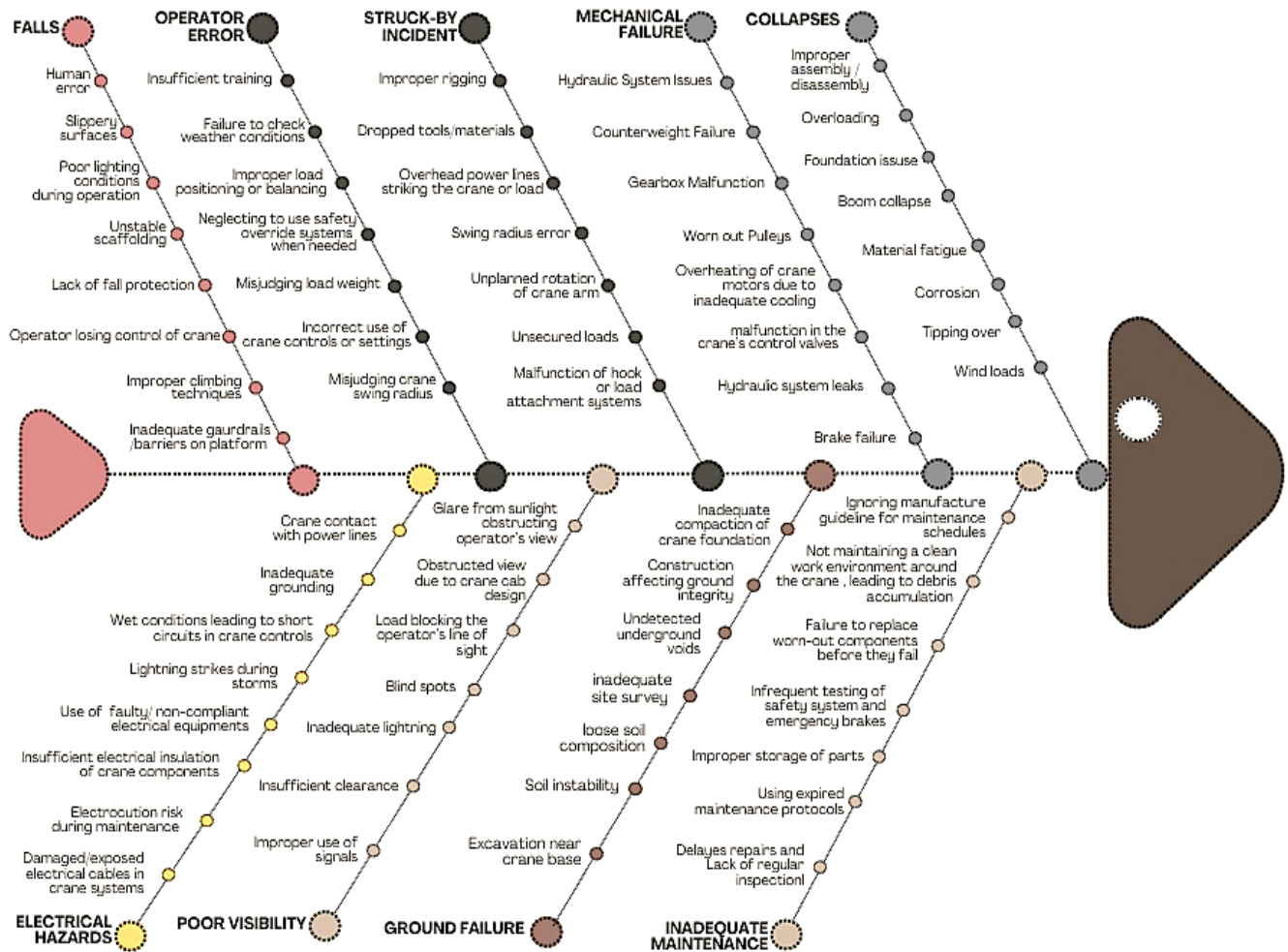


Fig. 1. Root causes of tower crane accidents fishbone diagram

Table 2. Severity matrix

	A Collapses	B Falls	C Struck-by incidents	D Electrical hazards	E Mechanical failures	F Operator errors	G Poor visibility	H Ground failure	I Inadequate maintenance
A Collapses	1								
B Falls	A3	1							
C Struck-by incidents	A3	C2	1						
D Electrical hazards	D4	D4	D3	1					
E Mechanical failures	A3	E2	E2	D3	1				
F Operator error	A2	B2	C2	D3	D3	1			
G Poor visibility	A3	B2	C2	D4	E4	G4	1		
H Ground failure	A3	H3	H3	D3	H3	H2	H2	1	
I Inadequate maintenance	I3	I2	I3	D4	I4	I3	I3	I3	1
Raw score	25	18	16	18	15	10	6	4	1
Adjusted total	3.73	4.08	3.49	2.49	2.16	2.08	1.83	1.33	1

Table 3. Likelihood matrix

		A Collapses	B Falls	C Struck- by incidents	D Electrical hazards	E Mechanical failures	F Operator errors	G Poor visibility	H Groun d failure	I Inadequate maintenance
A	Collapses	1								
B	Falls	B3	1							
C	Struck-by incidents	C2	B3	1						
D	Electrical hazards	A2	B3	C2	1					
E	Mechanical failures	E2	B3	C3	E3	1				
F	Operator error	F3	F3	F3	F3	F2	1			
G	Poor visibility	G2	B3	C3	G2	E2	F3	1		
H	Ground failure	H3	B3	C3	H2	H2	F3	H3	1	
I	Inadequate maintenance	I3	B4	I3	I3	I3	I3	I3	I2	1
	Raw score	21	23	18	14	10	10	7	3	1
	Adjusted total	4.32	3.23	3.15	2.99	2.83	1.99	1.66	1.5	1

Table 4. Detection matrix

		A Collapses	B Falls	C Struck- by incidents	D Electrical hazards	E Mechanical failures	F Operator errors	G Poor visibility	H Ground failure	I Inadequate maintenance
A	Collapses	1								
B	Falls	B3	1							
C	Struck-by incidents	C3	B2	1						
D	Electrical hazards	D4	B2	D3	1					
E	Mechanical failures	E2	B3	E2	D3	1				
F	Operator error	E3	E2	E2	D4	E3	1			
G	Poor visibility	G2	G2	G2	D3	E3	F3	1		
H	Ground failure	A2	B3	C3	D3	E2	F3	G2	1	
I	Inadequate maintenance	I3	B3	I3	D4	E3	F3	I3	I2	1
	Raw score	23	18	16	18	12	10	6	3	1
	Adjusted total	4.07	3.99	3.49	2.49	2.32	1.99	1.83	1.5	1

Table 5. Risk assessment checklist

Types of tower Crane Accidents	Risk score	Sub Causes	Hazard Criticality	Risk Priority Number (RPN)	Adjusted RPN (%)	Risk Rating	Adjusted Risk Rating
Collapses	65.58	Improper assembly/disassembly	12	24	19.2	2	9.60
		Overloading	9	18	14.4	2	7.20
		Foundation issues	8	16	12.8	2	6.40
		Crane collapse	12	24	19.2	2	9.60
		Boom collapse	12	36	28.8	3	21.60
		Material fatigue	6	18	14.4	2	7.20
		Corrosion	6	18	14.4	2	7.02
		Tipping over	8	24	19.2	2	9.60
		Wind loads	6	12	9.6	1	2.40
		Lack of fall protection	8	16	12.8	2	6.40
Falls	52.58	Improper climbing techniques	9	18	14.4	2	7.20
		Operator losing control of crane	9	27	21.6	2	10.08
		Unsecured ladders	4	8	6.4	1	1.60
		Poor lighting conditions during the operation	6	12	9.6	1	2.40
		Inadequate guardrails/barriers on the platform	6	12	9.6	1	2.40
		Unstable scaffolding	8	16	12.8	2	6.40
		Slippery surfaces	6	12	9.6	1	2.40
		Human error	8	24	19.2	2	9.60

Table 5. Risk assessment checklist (continued)

Types of tower Crane Accidents	Risk score	Sub Causes	Hazard Criticality	Risk Priority Number (RPN)	Adjusted RPN (%)	Risk Rating	Adjusted Risk Rating
Struck-by incidents	38.36	Improper rigging	9	18	14.4	2	7.20
		Inadequate communication	9	27	21.6	2	10.80
		Swing radius error	6	12	9.6	1	2.40
		Dropped tools/materials	6	18	14.4	2	7.20
		Malfunction of hook	6	18	14.4	2	7.20
		Overhead power lines striking the crane or load	8	24	19.2	2	9.60
		Unplanned rotation of crane arm	9	27	21.6	2	10.80
		Unsecured loads	9	18	14.4	2	7.20
		Crane contact with power lines	4	8	6.4	1	1.60
		Inadequate grounding	6	12	9.6	1	2.40
Electrical hazards	18.54	Wet conditions leading to short circuits in crane controls	8	24	19.2	2	9.60
		Lightning strikes during storms	4	12	9.6	1	2.40
		Use of faulty or non-compliant electrical equipment	8	16	12.8	2	6.40

Mechanical failures	14.18	Insufficient electrical insulation of crane components	3	9	7.2	1	1.80
		Electrocution risk during maintenance or repairs	8	24	19.2	2	9.60
		Damaged or exposed electrical cables in crane systems.	8	16	12.8	2	6.40
		Hydraulic system issues	9	18	14.4	2	7.20
		Counterweight failure	8	16	12.8	2	6.40
		Gearbox malfunction	9	18	14.4	2	7.20
		worn-out pulleys	6	18	14.4	2	7.20
		Overheating of crane motors due to inadequate cooling	6	12	9.6	1	2.40
		malfunction in the crane's control valves	9	18	14.4	2	7.20
		Hydraulic system leaks	9	18	14.4	2	7.20
Operator error	8.24	Brake failure	8	24	19.2	2	9.60
		Insufficient training	9	18	14.4	2	7.20
		Failure to check weather conditions	8	24	19.2	2	9.60
		Improper load positioning or balancing	9	18	14.4	2	7.20
		Incorrect use of crane controls or settings	9	18	14.4	2	7.20
		Neglecting to use safety override systems when needed	6	18	14.4	2	7.20
		Misjudging crane swing radius	6	12	9.6	1	2.40
		Misjudging load weight	9	18	14.4	2	7.20

Table 5. Risk assessment checklist (continued)

Types of tower Crane Accidents	Risk score	Sub Causes	Hazard Criticality	Risk Priority Number (RPN)	Adjusted RPN (%)	Risk Rating	Adjusted Risk Rating
Poor visibility	5.56	Blind spots	9	18	14.4	2	7.20
		Inadequate lighting	6	12	9.6	1	2.40
		Glare from sunlight obstructing the operator's view	6	12	9.6	1	2.40
		Obstructed view due to crane cab design	9	18	14.4	2	7.20
		Load blocking the operator's line of sight	9	18	14.4	2	7.20
		Insufficient clearance	6	12	9.6	1	2.40
		Improper use of signals	9	18	14.4	2	7.20
Ground failure	3	Excavation near crane base	12	28.8	56.3	3	21.60
		Soil instability	12	28.8	56.3	3	21.60
		Construction affecting ground integrity	12	19.2	37.5	2	9.60
		Inadequate compaction of the crane foundation	8	19.2	37.5	2	9.60

Inadequate maintenance	1	Undetected underground voids	8	12.8	25.0	2	6.40
		loose soil composition	9	14.4	28.1	2	7.20
		Inadequate site surveys	9	14.4	28.1	2	7.20
		Lack of regular inspections	9	27	21.6	2	10.80
		Delayed repairs	12	24	19.2	2	9.60
		Inadequate lubrication	6	18	14.4	2	7.20
		Using expired maintenance protocols	6	18	14.4	2	7.20
		Ignoring manufacturer guidelines for maintenance schedules	6	12	9.6	1	2.40
		Failure to replace worn-out components before they fail	12	24	19.2	2	9.60
		Not maintaining a clean work environment around the crane, leading to debris accumulation	9	18	14.4	2	7.20
		Infrequent testing of safety systems and emergency brakes	8	24	19.2	2	9.60
		Improper storage of parts	6	12	9.6	1	2.60

3. Results

As presented in Table 6, the results indicate that the most critical hazards in tower crane operations include collapses, struck-by incidents, electrical hazards, mechanical failures, operator errors, and inadequate maintenance, all characterized by high severity. Among these, mechanical failure and operator error exhibit both high severity and high likelihood, highlighting them as top-priority risks. Additionally, electrical hazards, though less likely, pose severe consequences and warrant close attention due to the difficulty of early detection. Poor visibility and falls, while rated with moderate severity, remain concerning due to their combined moderate likelihood and low detection potential. To mitigate these risks and enhance safety in tower crane operations, a multifaceted approach is essential. First, implementing rigorous preventive maintenance programs can significantly reduce the chances of mechanical failure and equipment-related incidents. Second, investing in comprehensive operator training and certification ensures that personnel are well-equipped to handle complex crane operations, thereby reducing human error. Enhanced safety protocols, including routine inspections and safety audits, should be enforced to detect potential issues early. Additionally, deploying advanced technologies such as anti-collision systems, real-time monitoring sensors, and automated safety alarms can improve detection capabilities. For visibility-related concerns, improved lighting and communication systems on site can mitigate risk. Collectively, these strategies foster a proactive safety culture and contribute to minimizing hazardous events in tower crane operations.

Table 6. Final results

Accident	Severity	Likelihood	Detection
Collapse	High	Moderate	Moderate
Falls	Moderate	Moderate	Low
Struck-by incidents	High	Moderate	Moderate
Electrical hazards	High	Low	Moderate
Mechanical failures	High	High	Moderate
Operator error	High	High	Moderate
Poor visibility	Moderate	Moderate	Low
Ground failure	High	Moderate	Moderate
Inadequate maintenance	High	Moderate	Moderate

4. Discussions

The integrated findings from the SLD matrix, Fishbone diagram, expert surveys, and risk assessment checklist emphasize that tower crane safety in high-rise construction requires a combination of technical, procedural, and behavioral interventions. Mechanical failures and operator errors emerged as critical risks, ranking high to moderate in severity, likelihood, and detection. Addressing these issues calls for strict adherence to preventive maintenance schedules that align

with manufacturer guidelines and industry best practices. Insights from surveys involving 100 professionals across 10 construction sites highlighted the importance of simulation-based training programs to strengthen operator competency and minimize judgment-related errors.

Furthermore, the Fishbone analysis revealed systemic weaknesses such as inadequate inspections, delayed repairs, and procedural lapses, which can be mitigated through regular safety audits, timely replacement of critical components, and the use of real-time inspection tracking systems. Hazards with low detection potential, particularly poor visibility and falls, demand context-sensitive interventions like enhanced site lighting, strategic crane positioning, and tailored safety assessments. The integration of digital tools, such as real-time monitoring systems and electronic safety logs, offers additional opportunities to improve early detection of malfunctions and deviations. Collectively, these insights point to the need for a risk-prioritized, site-specific, and technologically enabled safety management strategy.

5. Conclusion

This study shows that tower crane safety in high-rise construction depends on a multi-faceted, risk-based approach. Preventive maintenance, operator training, inspections, and digital monitoring are essential to address mechanical and human-related failures. By targeting high-risk hazards and enhancing detection, accident potential can be reduced while strengthening safety culture. The proposed framework offers practical guidance locally and can be adapted to varied regulatory and construction contexts globally. Although this study is framed within a local context, the methodological approach, using the SLD matrix and structured risk assessment checklist, can be adapted to different regions and countries. Tower crane hazards, while influenced by site-specific variables, are common across the globe, and the framework allows recalibration based on local regulatory standards, workforce practices, and environmental conditions. By tailoring the scoring criteria and implementation strategies, practitioners worldwide can employ these findings to enhance crane safety in high-rise construction. Thus, the results provide not only local insights but also a transferable foundation for advancing globally relevant safety strategies.

Limitations of the current study include potential data constraints, as risk assessment is dependent on available incident reports, and these might not be comprehensive. The proposed model may not account for all site-specific variables, thereby limiting generalizability. Furthermore, the model's effectiveness depends on proper implementation, regulatory adherence, and adoption by the workforce. Further research must consider more advanced hazard identification methods for tower crane operations, incorporating real-time monitoring and predictive analysis. Proactive strategies such as real-time weather alerts and continuous visual monitoring could significantly reduce the likelihood of tower crane accidents. Enhancements in machine learning for risk assessment models may further enhance precision. Moreover, constructing proactive countermeasures, integrating automation, and streamlining safety regulations will contribute to safer and more efficient crane operations.

Authors' contribution

Aarya Shah was responsible for project planning, execution, methodology, data collection, analysis, visualization, and manuscript drafting. Lukman E Mansuri contributed to conceptualization, idea generation, supervision, and overall guidance throughout the research process. He provided critical insights, reviewed progress, and ensured the quality and direction of the work. Both authors have read and approved the final version of the manuscript for submission and publication.

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