ISSN 1392-3730/eISSN 1822-3605

JOURNAL of CIVIL ENGINEERING and MANAGEMENT

2026
Volume 32
Issue 6
Pages 854–868
https://doi.org/10.3846/jcem.2026.27814

CRITICAL RISK FACTORS FOR MOBILE CRANE SAFETY IN HONG KONG VIA A MIXED-METHODS STUDY

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Article History:
- received 4 February 2026
- accepted 5 May 2026

Abstract. Mobile crane accidents in Hong Kong, particularly those involving civil and road works, often result in fatalities, with the most common type being workers struck by falling or flying objects. This study adopted a mixed analysis process to identify critical risk factors for mobile crane safety and formulate effective safety recommendations in Hong Kong. A questionnaire survey was conducted among 509 construction workers to identify critical risk factors affecting mobile crane safety, followed by risk factors ranking by severity index analysis. Focus group meetings were conducted among 11 senior experts to validate these critical risk factors and to propose practical strategies to reduce the risk of mobile cranes in Hong Kong. It is found that communication during lifting operations, crane operator safety awareness, and main contractor safety management are the major critical risk factors for mobile crane safety. The mechanisms underlying these factors are discussed, along with practical recommendations to mitigate safety issues related to mobile cranes in Hong Kong, emphasizing communication, training, safety culture, and regulation updates. These findings highlight crucial areas for intervention, providing a roadmap to enhance safety within the construction industry, ultimately aiming to reduce accidents and improve overall operational safety.

Keywords: mobile crane, Rasmussen's risk management framework, risk factors, questionnaire survey, focus group.

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1. Introduction

The construction industry plays a vital role in national and global economies, but it is notably dangerous. In the United States, construction workers accounted for 1,075 fatalities in 2023, representing 20.35% of all fatal work injuries, marking the highest rate of fatal accidents among various industrial sectors (U.S. Bureau of Labor Statistics, 2024). Similarly, in Hong Kong, the construction sector recorded an accident rate of 10.61% in 2024, second only to the food service industry, with 3,037 reported accidents (Hong Kong Labour Department, 2025). As construction environments become increasingly mechanized, reliance on mobile cranes for lifting and transporting materials has intensified (Shapira et al., 2007). Mobile cranes are essential for their high mobility and ability to maneuver heavy components in constrained spaces. However, this mobility introduces specific hazards, such as tip-overs and operational risks (Lee et al., 2022; Kim & Kang, 2022; Romanello, 2022). Notably, crane-related accidents often involve not only operators and riggers but also construction workers and the public. From 1997 to 2004, 88% of crane-related accidents in the U.S. involved mobile cranes (Beavers et al., 2006), with similar trends observed globally, where mobile cranes accounted for 72% of crane safety incidents from 2011 to 2015 (Milazzo et al., 2017). In Hong Kong, the rise of modular integrated construction (MiC) has led to increased mobile crane deployment, yet safety concerns persist. Between 2015 and 2022, 18 crane-related fatalities occurred, 16 of which involved mobile cranes (Hong Kong Labour Department, 2024). Despite the critical nature of these issues, research on mobile crane risk factors and safety measures in Hong Kong remains limited.

Mobile crane safety issues can be viewed as a complex sociotechnical system, encompassing various technical, environmental, and social components that necessitate systematic thinking and analysis. To enhance mobile crane safety and effectively prevent injury accidents, scholars primarily adopt two complementary approaches for reactive accident analysis and proactive risk modelling to identify and analyze crucial risk factors. Studies like Kan et al. (2018) and Lee et al. (2022) systematically categorize direct causes (e.g., collisions, tip-overs) and contributing factors (e.g., human error, mechanical failures) through taxonomic analysis of historical incidents, highlighting riggers as high-risk groups and procedural violations as recurrent issues. A modified management framework for economic, physical, political, and social (MEPS) was developed from 56 accident reports, underscoring systemic gaps in safety training and compliance from Kim and Kang (2022). While these analyses elucidate past failure mechanisms, their retrospective nature limits predictive capability for the novel or evolving hazards. Conversely, proactive frameworks have been developed to enable preemptive management by synthesizing specialized risk factors, such as environmental instability and load dynamics. Notable examples include the systemic factor taxonomy (Zhou et al., 2018) and the crane operation risk directory (CORD) (Sadeghi et al., 2021).

Despite extensive research on mobile crane safety, three critical gaps remain. First, existing studies predominantly focus on technical failures and equipment specifications, overlooking the sociotechnical system interactions among government regulators, contractors, and operators. Second, methodological limitations persist, with most studies relying on small-scale case analyses or accident reports, lacking large-scale empirical data and mixed-methods approaches. Third, geographical bias exists, as research has concentrated on Western and East Asian contexts, neglecting the unique challenges of high-density Asian cities like Hong Kong. Hong Kong presents a distinctive context characterized by extreme spatial constraints, a hybrid regulatory environment, and rapid adoption of modular construction. The average construction site area in Hong Kong is significantly smaller than in other international cities, creating unprecedented challenges for mobile crane operations.

This study addresses these gaps by developing a comprehensive risk factor framework for mobile crane safety in Hong Kong, integrating quantitative survey data from 509 industry professionals with qualitative insights from expert focus groups. The research contributes theoretically by adapting Rasmussen's sociotechnical framework to high-density urban construction, methodologically by employing a large-scale mixed-methods approach, and practically by providing actionable recommendations for Hong Kong's regulatory authorities and construction industry. While the empirical context is Hong Kong-specific, the methodological approach and the structured framework offers transferable insights for other high-density cities facing similar challenges.

2. Literature review

2.1. Construction risk management model

Risk management constitutes a systematic process vital for identifying hazards, assessing associated risks, and implementing control measures within construction projects (Trethewy et al., 2003; Wang et al., 2016). Its effectiveness is paramount for achieving objectives concerning time, cost, quality, and safety (Nketekete et al., 2016). While project managers are advised to continuously monitor risks from initiation to completion (Obondi, 2022), practical reliance on standardized checklists often proves inadequate for addressing unique project characteristics, such as specific site conditions and stakeholder dynamics (Al Qudah et al., 2024). Consequently, the development of scientific risk management models has become a focal point, aiding organizations in planning, implementing, and evaluating preventive measures (Sun et al., 2008; Shi et al., 2019). The core challenge lies not in managing every conceivable risk, but in identifying and prioritizing critical risks for efficient resource allocation (El-Sayegh & Mansour, 2015).

To operationalize risk management, diverse analytical frameworks have been established. Sun et al. (2008) adopted the Analytic hierarchy process (AHP) to create a safety risk assessment model focused on managerial aspects like organization, planning, and emergency response. In a complementary vein, Shi et al. (2019) developed a safety risk management objective system based on accident causation theory, emphasizing human and cultural factors through sub-objectives such as organization, culture, and talent. While these models enhance systematic safety analysis, their focus remains largely internal, often neglecting the significant influence of external, upstream factors, particularly governmental and regulatory decisions. In contrast, Rasmussen's risk management framework offers a more holistic, sociotechnical lens by conceptualizing safety performance across a hierarchy of six levels: government, regulators and associations, companies, management, staff, and the work level (Rasmussen, 1997). This framework posits that accidents result from a loss of control over hazardous processes, influenced by dynamic interactions across all levels within broader technical, economic, and policy contexts. Its comprehensive nature has proven foundational for modeling complex systems. Subsequent studies by Zhou et al. (2018) and Goncalves Filho et al. (2021) have successfully adapted and validated its utility for systemic construction safety analysis.

This paper adopts Rasmussen's framework as a categorization model for identifying contributing factors for the following reasons. First, it encompasses factors beyond the organizational level, including external influences such as governmental policies and technical issues. In addition, Rasmussen's framework is more manageable for adoption than other accident analysis methods (Zhou et al., 2018; Goncalves Filho et al., 2021). However, due to the unique context of Hong Kong, this study combines Level 1 (Government) and Level 2 (Regulators), with the Hong Kong Labour Department and other relevant agencies representing regulatory control and influence.

2.2. Contributing factors affecting mobile crane safety

Research on mobile crane safety has evolved through two primary methodological approaches: retrospective accident analysis and prospective risk modeling. Studies analyzing historical accident data have consistently identified critical risk patterns, with research by Beavers et al. (2006) establishing that inadequate safety performance among crane operators and riggers constitutes a significant causative factor. Expanding on this, Kan et al. (2018) developed a taxonomic classification of 325 mobile crane accidents, identifying specialized hazards including collisions, overloading, and tip-overs. More recent work by He et al. (2025) has advanced this field through scenario analysis theory, investigating crane accidents through an integrated human-machine-environment-management lens, thereby providing a more holistic analytical framework. Cross-national studies by Lee et al. (2022) in South Korea and Hamid et al. (2019) in Malaysia further validated these findings, highlighting human error and mechanical failures as predominant causes, with riggers being particularly vulnerable. Kim and Kang (2022) applied a modified MEPS framework to accident reports, revealing systemic deficiencies in procedural compliance and safety training as underlying contributors.

Complementing reactive analyses, proactive frameworks aim to identify latent risk factors before incidents occur. Zhou et al. (2018) adapted Rasmussen's socio-technical framework to develop a hierarchical risk model for crane operations, enabling systematic analysis across multiple organizational levels. Sadeghi et al. (2021) subsequently synthesized existing research into a comprehensive CORD, integrating specialized risk factors spanning technical failures, environmental conditions, load dynamics, unsafe worker behaviors, and organizational factors such as communication protocols and training adequacy. This integrated approach represents a significant advancement in moving beyond isolated factor analysis toward a more systemic understanding of crane safety, with He et al.'s (2025) scenario analysis providing a contemporary methodological innovation in this domain. To systematically identify the risk factors for this study, a rigorous literature review was conducted following a systematic approach. We synthesized factors from seminal works, particularly the comprehensive CORD developed by Sadeghi et al. (2021), which aggregates risk factors from numerous previous studies. This process ensured that the initial factor pool was exhaustive and grounded in established research.

Prior research has promoted the development of targeted preventive strategies for mobile crane accidents. However, these studies have primarily adopted a reductionist approach, focusing on identifying individual factors affecting mobile crane safety, while systems thinking in this context remains underexplored. Additionally, the absence of specialized critical risk factors in Hong Kong underscores the need for tailored strategies to enhance mobile crane safety in the region. This research aims to address this gap by providing a comprehensive examination of mobile crane safety factors specific to Hong Kong. A questionnaire survey involving construction workers in Hong Kong will help identify the critical risk factors associated with mobile cranes in the local context. Furthermore, an FG meeting with senior experts will facilitate the development of suitable and effective strategies to tackle mobile crane safety issues in Hong Kong. By integrating these methodologies, the study seeks to contribute to more effective accident prevention strategies and enhance overall safety protocols within the construction industry.

3. Risk management model of mobile crane

A systematic mobile crane safety analysis framework was developed through a two-stage process, used to identify safety hazards and contributing factors. Initially, a comprehensive systematic review of the literature was conducted to identify potential risk factors. Based primarily on the comprehensive inventory provided in Sadeghi et al. (2021), a total of 56 contributing factors relevant to mobile crane safety were initially identified. Subsequently, these factors were adapted to the specific context of Hong Kong. Five factors specifically related to tower cranes (e.g., foundation stability, working at height) and the roles of erection and dismantling workers were excluded. Additionally, factors concerning "collision-free maneuvering for crawler cranes" were deemed unsuitable for Hong Kong's confined sites and were therefore removed. As a result, the remaining 50 contributing factors were consolidated into 33 based on their similarities, creating a more streamlined framework for evaluating mobile crane safety within Hong Kong's construction industry. Finally, to provide a structured theoretical basis, the 33 consolidated factors were categorized according to Rasmussen's risk management framework into five levels: 1) government and regulatory bodies, 2) stakeholders, 3) site management, 4) workers and staff, and 5) work environment and equipment. The modified major safety risk factors for mobile cranes in Hong Kong are illustrated in Table 1.

4. Research methodology

4.1. Research framework

This study employed a mixed-methods approach to systematically identify and validate critical risk factors affecting mobile crane safety in Hong Kong. As outlined in Figure 1, the research initiated with the development of a risk factor model grounded in Rasmussen's framework, which subsequently guided the design and distribution of a structured questionnaire to construction professionals.

Table 1. Major safety risk factors for mobile cranes in Hong Kong

No.	Factor	References
1.	Government and management	
1.1.	Government safety regulation & supervision	Sadeghi et al. (2021), Ji and Leite (2018), Sertyesilisik et al. (2010)
1.2.	Government safety regulator: operator certification	Xu et al. (2020), Sadeghi et al. (2021), Kim and Kang (2022)
1.3.	Government safety regulator: crane registration	Tam and Fung (2011), Im and Park (2020), Sadeghi et al. (2021), Kim and Kang (2022)
2.	Stakeholders	
2.1.	Main contractor: safety management and input	Sadeghi et al. (2021), Raviv et al. (2017), Raviv and Shapira (2018)
2.2.	Main contractor: safety attitude	Wu et al. (2016), Chan et al. (2018), Sadeghi et al. (2021)
2.3.	Subcontractor: crane safety input	Feng (2013), Sadeghi et al. (2021), Esmaeili et al. (2021)
2.4.	Manufacturers qualifications	Swuste (2013), Sadeghi et al. (2021), Kim and Kang (2022)
3.	Management of the Construction site during the work process	
3.1.	Main contractor: safety plan and site supervision	Li and Liu (2012), Han et al. (2018), Taghaddos et al. (2019)
3.2.	Main contractor: safety training and daily briefing	Sadeghi et al. (2021), Shringi et al. (2022), Lee and Jung (2022)
3.3.	Main contractor: reward and punishment	Guo et al. (2018), Sadeghi et al. (2021), Liu et al. (2022), Feng et al. (2023)
3.4.	Main contractor: safety acceptance of crane safety requirements	Sadeghi et al. (2021), Kim and Kang (2022), Zhong et al. (2025)
3.5.	Subcontractor: safety training and daily briefing	Li and Liu (2012), Teizer et al. (2013), Sadeghi et al. (2021)
3.6.	Subcontractor: inspection, checking, and crane maintenance	Mohammadi et al. (2021), Sadeghi et al. (2021), Kim and Kang (2022)
3.7.	Subcontractor: safety plans for crane operation, including ground conditions and working space issues	Sadeghi et al. (2021), Kim and Kang (2022), Kargar et al. (2022), Guo et al. (2022)
3.8.	Working schedule pressure	Han et al. (2018), Taghaddos et al. (2019), Sadeghi et al. (2021)
3.9.	Warning region setting	Chae and Yoshida (2010), Sitompul et al. (2020), Sadeghi et al. (2021)
4.	Workers and staff on construction sites	
4.1.	Supervisor: character and safety commitment	Zhang et al. (2020), Sadeghi et al. (2021), Wu et al. (2024a), Sankar et al. (2024)
4.2.	Supervisor: safety inspection and instruction	Galindo et al. (2013), Sadeghi et al. (2021), Wang et al. (2024)
4.3.	Signaller: safety awareness and direction	Sadeghi et al. (2021), Kim and Kang (2022), Sruthy and Xavier (2023)
4.4.	Rigger: safety awareness and operation	Sadeghi et al. (2021), An (2022), Kim and Kang (2022), Lee et al. (2022)
4.5.	Crane operator: safety awareness and operation	Fang et al. (2016), Man et al. (2019), Sadeghi et al. (2021), Wu et al. (2024b)
4.6.	Crane operator: routine checking	Beavers et al. (2006), Sadeghi et al. (2021), Kim and Kang (2022)
4.7.	Crane operator: physical and mental health	Spasojević Brkić et al. (2016), Afshari et al. (2021), Sadeghi et al. (2021)
4.8.	Workers: safety values, job stress, and ability	Teizer et al. (2013), Fang and Cho (2017), Sadeghi et al. (2021)
4.9.	Communication during the lifting operation	Zhang and Hammad (2012), Hung et al. (2016), Han et al. (2017)
5.	Environment and equipment	
5.1.	Cross operation – simultaneous activities or overlapping crane works	Lai and Kang (2009), Han et al. (2015), Taghaddos et al. (2019)
5.2.	E3:Crane operator – aids, e.g., CCTV, RFID sensor, computerized safe load indicators, etc.	Hwang (2012), Han et al. (2015), An et al. (2018)
5.3.	Reliability of the crane safety device, assembling auxiliary equipment, and the attachment device	Beavers et al. (2006), Sadeghi et al. (2021), Kim and Kang (2022)
5.4.	Reliability of crane structural parts and crane ergonomics	Araya et al. (2004), Romanello (2018), Sadeghi et al. (2021)
5.5.	Blind lifting and visibility	Chen et al. (2017), Sadeghi et al. (2021), Li et al. (2023)
5.6.	Obstacles and congested site	Han et al. (2017), Sadeghi et al. (2021), Li et al. (2025)
5.7.	Weather phenomena – temperature, humidity, wind	Sun et al. (2009), Sadeghi et al. (2021), Schuldt et al. (2021), Šopić et al. (2025)
5.8.	Ground conditions (working closely with power lines)	Al-Humaidi and Tan (2009), Romanello (2018), Sadeghi et al. (2021)

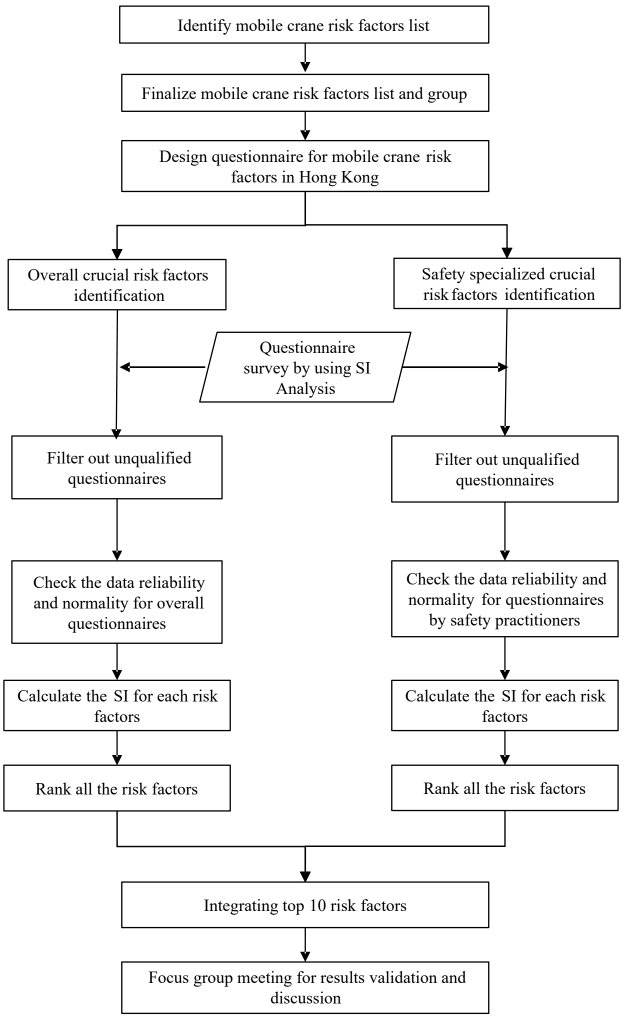

Figure 1. Research framework of the study

The Severity Index (SI) method was applied to rank the identified risk factors, and the resulting preliminary rankings were further examined and validated through focus group discussions involving senior industry experts. These discussions not only confirmed the quantitative findings but also yielded practical, context-specific recommendations. The integration of quantitative assessment and qualitative insights strengthened the validity of the results and provided a solid foundation for developing targeted safety strategies applicable to Hong Kong's construction environment.

4.2. Questionnaire survey

4.2.1. Data collection

Data were collected via a structured questionnaire derived directly from the 33 risk factors in Table 1. In line with methodological guidelines (Hair et al., 2019), a target sample size of 500 was set to robustly analyze the 33 factors, exceeding the recommended minimum of 330. The sampling strategy involved contacting over 10 main contractors and assessing more than 40 sites to ensure diverse participation and improve the generalizability of the results.

In total, 636 questionnaires were returned. After imputing missing values and deleting the unengaged responses, 509 valid questionnaires were shortlisted for review and further analysis, resulting in a usable rate of 80.03%. This exceeds the 67% return rate benchmark proposed by Othman et al. (2021), indicating an acceptable level of participation. Demographic analysis of the survey data (Figure 2) revealed that the majority of the participants were male (89.00%), over 35 years old (69.55%), and had received at least a secondary school education (92.93%). In terms of expertise, safety practitioners formed the largest group (32.22%), followed by management staff and crane operators. Importantly, the data reflects substantial field experience, with 73.57% of respondents possessing over five years in construction and 57.37% having specific involvement in lifting operations, thereby lending significant credibility to the collected data.

4.2.2. Data analysis

Data analysis was performed using SPSS (v.28.0). Scale reliability was confirmed with Cronbach's alpha coefficients of 0.966 (overall) and 0.975 (safety practitioners), indicating high internal consistency (George & Mallery, 2024). Descriptive statistics were employed as the primary analytical approach.

The relative importance of risk factors was ranked using the Severity Index (SI), which ranges from 0 to 1 (higher values indicate greater importance) (Chen et al., 2010).

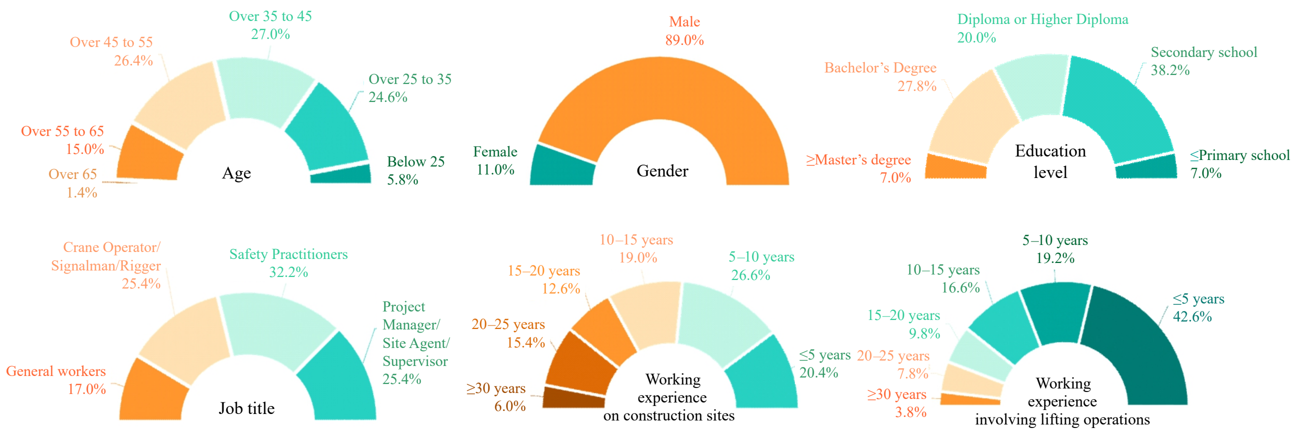

Figure 2. Profile of respondents

To facilitate the interpretation and prioritization of risks, factors with an SI value greater than 0.8 were considered high-risk, following established benchmarks (Chen et al., 2010). The complete SI values and the corresponding risk levels (High: SI ≥ 0.8; Medium: 0.6 ≤ SI < 0.8; Low: SI < 0.6) for all factors are presented in Table 3. The SI for risk factors *n* is determined from the survey using the following equation:

$$SI_{rf_n} = \frac{\sum_{i=1}^{5} L_i \cdot \frac{f_i}{N}}{\beta}, \tag{1}$$

where L_i represents the Likert scale point (1–5), f_i is the response frequency for that point, N is the total number of valid responses (509), and β is the highest scale point (5).

To capture the unique insights of key safety stakeholders, separate SI analyses were conducted for safety practitioners. Their distinct roles as policy implementers, supervisors, and trainers endow them with a critical perspective on risk, influencing safety intervention design. To statistically examine the differences in risk perception between the overall sample and safety practitioners, independent samples t-tests were conducted for each of the 33 risk factors. The resulting p-values (presented in Table 3) indicate whether the observed differences in mean SI scores are statistically significant ($p < 0.05$). The rankings derived from these analyses were subsequently validated and enriched through literature review and focus group discussions, as detailed in Section 5.

4.3. Focus group meeting

4.3.1. Data collection

To validate and contextualize the quantitative findings from the SI analysis, a FG meeting was conducted following established methodological guidelines (Gelo et al., 2008). The primary objectives were to review the ranked risk factors, explore their underlying mechanisms, and develop practical mitigation strategies tailored to the Hong Kong context.

The FG meeting was conducted in a hybrid format that accommodated both face-to-face and online participation. Eleven experts with a minimum of 20 years of experience in construction and lifting operations were selected to ensure diverse perspectives (Yang et al., 2019). The participants represented key stakeholder groups, including safety consultants, main contractors, and crane specialists, as detailed in Table 2. To maximize discussion efficiency, the meeting agenda and preliminary results were distributed to all participants one week in advance. During the group discussion, participants engaged with set topics, expressing their ideas and providing feedback on new information presented by other members. This collaborative approach allowed for the exploration of viable opinions and recommendations, which assisted in validating and enriching the proposed strategies for improving mobile crane safety in Hong Kong.

4.3.2. Data analysis

The focus group data were analysed through a systematic, four-stage qualitative content analysis (Krueger, 2014). The process was rigorously applied to derive the specific findings presented in Sections 5.2 and 6. After verbatim transcription, initial coding was explicitly guided by the top-ranked risk factors from the survey, such as communication breakdowns and contractor safety attitudes. The subsequent thematic analysis crystallized key patterns, including the critical importance of pre-lift briefings and the impact of schedule pressure on management commitment – themes that directly explain the high quantitative rankings. The crucial integration phase involved

Table 2. Background of focus group members (source: author's own creation)

ID	Position (title)	Organization	Number of years in the construction industry	Number of years involved in the lifting operation
1	Safety Consultant (Ex-officer of the Labour Department)	Safety Consultant	Over 30	Over 30
2	Senior Instructor	HK Institution of Construction, Construction Industry Council	26	26
3	Chief Project Safety Manager	Client (MTR)	Over 20	Over 20
4	Cooperate & Safety Director	Main Contractor	Over 30	Over 30
5	Head of Safety	Main Contractor (Mainly for foundation works)	27	Over 20
6	Assistant to General Manager	Main Contractor (Mainly for foundation works)	20	8
7	Senior Project Manager	Main Contractor (Mainly for building works)	29	29
8	Deputy General Manager, Safety and Environment Department	Main Contractor	23	23
9	Assistant General Manager (Plant Department)	Main Contractor	30	23
10	Company Owner	Crane Rental Company	45	45
11	Director	Crane Rental Company	40	40

mapping these nuanced insights against the SI rankings; for instance, experts' detailed accounts of on-site communication challenges validated the top ranking of factor B4.9 and provided the contextual depth behind the statistical result. Finally, these integrated findings were translated into the actionable strategies outlined in Section 6, such as the recommendation for bidirectional communication protocols. This methodical process ensured that every qualitative insight was grounded in and directly addressed the quantitative findings, solidifying the validity and practical relevance of the study's conclusions.

5. Results and discussion

5.1. Results from questionnaire survey

As presented in Table 3, the SI analysis identified twenty-nine factors falling into the high-risk category (SI ≥ 0.8), and four factors as medium-risk (0.6 ≤ SI < 0.8). Statistical comparison via independent samples t-tests revealed significant differences ($p < 0.05$) in the perception of several factors between the overall respondents and safety practitioners. For instance, factors such as "Government safety regulation & supervision" (B1.1) and "Subcontractor: safety input" (B2.3) showed significantly lower SI scores among safety practitioners compared to the general workforce, suggesting that experts might underestimate certain regulatory and subcontractor-related risks. Conversely, factors like "Main contractor safety attitude" (B2.2) and "Crane operator routine checking" (B4.6) did not show statistically significant differences ($p > 0.05$), indicating a strong consensus across different stakeholder groups regarding the criticality of these operational and managerial factors. Section 5.2 provides a detailed discussion of the top ten high-risk factors, which represent the most severe threats to mobile crane safety in Hong Kong.

5.2. Discussion on the top factors

The identification of the top ten critical risk factors provides valuable insights into the primary safety concerns in mobile crane operations. This section discusses the implications of these findings in relation to existing literature and industry practices.

5.2.1. Communication during lifting operations (B4.9)

All groups, except for general workers, identified communication as one of the top two critical safety factors for mobile crane operation, as shown in Table 3. This consensus underscores the necessity of establishing effective and dual communication among all relevant personnel, including crane operators, signallers, riggers, workers, and lifting supervisors, to ensure safe crane operations. This finding aligns with the study by Tam and Fung (2011), where 94.1% of respondents emphasized the importance of crane operators, riggers, and signallers fully understanding radio and telecommunication signals among crew members. Furthermore, Mansoor et al. (2022) highlighted that improper communication is a major cause of mobile crane accidents, emphasizing the need for clear and effective communication protocols. Effective communication must operate through dual channels, facilitating a clear exchange of information. Lingard et al. (2014) pointed out that the quality of communication directly influences the quality of risk control outcomes. Therefore, communication during lifting operations must occur continuously and effectively throughout the entire lifting process, encompassing each phase from planning to execution. This holistic approach not only enhances operational safety but also fosters a culture of collaboration and awareness among all team members involved in lifting operations.

5.2.2. Main contractors: safety management and input (B2.1) and safety attitude (B2.2)

All groups ranked the "main contractors: safety attitude" as one of the top ten critical factors affecting mobile crane safety, and Group 2 – safety practitioner ranked the "main contractors: safety management and input" as similarly critical. The main contractor plays a pivotal role as the principal entity responsible for site progress, as well as for establishing and implementing the safety management system for construction projects. These findings align with previous research, which indicates that organizations where leaders actively promote occupational safety experience lower accident rates and improved safety performance (Shannon et al., 1997; Stiles et al., 2018). Qayoom and Hadikusumo (2019) and Wang et al. (2016) further highlighted that the behaviour and attitude of top management towards safety significantly influence workers' risk tolerance. When safety regulations are enforced through in-house rules, mandatory supervision, and stringent penalties for unsafe behaviours, workers typically exhibit lower safety risk tolerance (Wang et al., 2016).

Moreover, safety requirements can be integrated into contract clauses between the main contractor and crane companies (Sadeghi et al., 2021). In Hong Kong, where most mobile cranes are outsourced to specialized crane companies, the main contractor can substantially influence the safety behaviours of crane operators and related personnel through contract stipulations, in-house safety regulations, and detailed lifting plan requirements. Furthermore, owing to technological advances, many kinds of planning and real-time monitoring systems can be created to offer advantages of effective planning, proactive monitoring of crane operations, crane and operator feedback, and reduction in mobile crane failures (Kan et al., 2018).

5.2.3. Factors related to crane operator (B4.5, B4.6 and B4.7), signaller (B4.3), and rigger (B4.4)

Five of the top ten identified critical factors affecting mobile crane safety are directly related to the roles of the crane operator, signaller, and rigger. These findings underscore the consensus across all groups that human factors, particularly the safety attitudes and awareness of front-

Table 3. Ranking of critical factors on mobile crane safety in Hong Kong from overall responses (source: author's own creation)

Factor	Overall response				Safety practitioners' response			P-value (T-test)
	Number	SI	Rank	Risk level	Number	SI	Rank	
B1 Government and Regulatory Bodies								
B1.1 Government safety regulation & supervision	509	0.8212	27	High	164	0.8646	15	0.0003
B1.2 Government safety regulator: operator certification	509	0.8259	24	High	164	0.8524	22	0.0231
B1.3 Government safety regulator: crane registration	509	0.8271	23	High	164	0.8512	23	0.0409
B2 Stakeholders								
B2.1 Main contractor: safety management and input	509	0.8519	11	High	164	0.8744	9	0.0346
B2.2 Main contractor: safety attitude	509	0.8648	3	High	164	0.8854	5	0.0512
B2.3 Subcontractor: crane safety input	509	0.8401	14	High	164	0.872	11	0.0042
B2.4 Manufacturers qualifications	509	0.8251	25	High	164	0.8305	29	0.6521
B3 Management of construction sites								
B3.1 Main contractor: safety plan and site supervision	509	0.8405	12	High	164	0.8549	19	0.1774
B3.2 Main contractor: safety training and daily briefing	509	0.8145	28	High	164	0.8427	25	0.0138
B3.3 Main contractor: reward and punishment	509	0.7505	33	Medium	164	0.7537	32	0.8036
B3.4 Main contractor: safety acceptance of crane safety requirements	509	0.8354	17	High	164	0.8427	25	0.4909
B3.5 Subcontractor: safety training and daily briefing	509	0.8287	22	High	164	0.8573	17	0.0122
B3.6 Subcontractor: inspection, checking, and crane maintenance	509	0.8554	10	High	164	0.889	3	0.0018
B3.7 Subcontractor: safety plans for crane operation, including ground conditions and working space issues	509	0.8597	5	High	164	0.8817	7	0.0406
B3.8 Working schedule pressure	509	0.7851	31	Medium	164	0.7963	30	0.3845
B3.9 Warning region setting	509	0.8338	19	High	164	0.8659	14	0.0057
B4 Workers and staff on the construction site								
B4.1 Supervisor: character and safety commitment	509	0.8369	16	High	164	0.8549	19	0.1014
B4.2 Supervisor: safety inspection and instruction	509	0.8338	19	High	164	0.8573	17	0.0313
B4.3 Signaller: safety awareness and direction	509	0.8582	7	High	164	0.8841	6	0.0231
B4.4 Rigger: safety awareness and operation	509	0.8644	4	High	164	0.8878	4	0.0315
B4.5 Crane operator: safety awareness and operation	509	0.8762	1	High	164	0.9024	1	0.0171
B4.6 Crane operator: routine checking	509	0.8574	8	High	164	0.8707	12	0.2262
B4.7 Crane operator: physical and mental health	509	0.8593	6	High	164	0.8744	9	0.1703
B4.8 Workers: safety values, job stress, and ability	509	0.8405	12	High	164	0.6012	33	0.4043
B4.9 Communication during lifting operation	509	0.8762	1	High	164	0.8988	2	0.0441
B5 Environment and equipment								
B5.1 Cross operation – simultaneous activities or overlapping crane works	509	0.8138	29	High	164	0.8683	13	<0.0001
B5.2 Crane operator – aids, e.g., CCTV, RFID sensor, computerized safe load indicators, etc.	509	0.7886	30	Medium	164	0.8537	21	0.0125
B5.3 Reliability of crane safety devices, assembling auxiliary equipment, and attachment devices	509	0.8346	18	High	164	0.8402	27	0.6093
B5.4 Reliability of crane structural parts and crane ergonomics	509	0.8566	9	High	164	0.878	8	0.0495
B5.5 Blind lifting and visibility	509	0.8326	21	High	164	0.8634	16	0.0087
B5.6 Obstacles and congested site	509	0.8228	26	High	164	0.8512	23	0.0181
B5.7 Weather phenomena – temperature, humidity, wind	509	0.7646	32	Medium	164	0.7805	31	0.2069
B5.8 Ground conditions (working closely with power lines)	509	0.8397	15	High	164	0.8378	28	0.8657

line workers, are the most critical determinants influencing mobile crane operations. According to King (2012), 43% of the crane accidents from 2004 to 2010 were due to the crane operator's failure in their responsibilities. Similarly, Raviv et al. (2017) found that four of the top five failure types were linked to human factors: inattention (19%), improper rigging (15%), operator error (13%), and error of the signal person (11%). These insights highlight the significant impact of human factors on safety outcomes in crane operations. The results from Raviv et al. (2017) resonate with the findings of this study, reinforcing the notion that human factors are paramount compared to other influences, such as technical or environmental factors, when assessing the degree of hazard.

5.2.4. Factors related to crane subcontractor (B3.6 and B3.7)

Safety input, particularly concerning crane inspection, checking, and maintenance by the crane subcontractor, emerges as a critical factor in enhancing mobile crane operation safety. Lee and Foo (2022) found that some crane accidents were related to an error in safety inspection, or pre-operation inspection was not performed correctly. This highlights the essential need for rigorous checking and inspection protocols to be followed before crane use. According to the Code of Practice for the Safe Use of Mobile Cranes issued by the Labour Department, it is the responsibility of the crane owner to ensure that all personnel involved in the preparation, erection, operation, and use of the mobile crane are adequately trained in safety and operational procedures. Furthermore, the crane owner is tasked with ensuring that thorough maintenance and inspection of the crane are conducted regularly, and that the crane and associated equipment comply with the manufacturer's specifications and all relevant regulations, as emphasized by the Construction Safety Association of Ontario.

5.2.5. Reliability of crane structural parts and crane ergonomics (B5.4)

The stability of a crane during operation is intrinsically linked to the reliability of its structural components. Sadeghi et al. (2021) stated that enhancing the reliability and quality of the crane and its accessories, such as the jib and boom, significantly improves safety performance during crane operations. Another critical factor influencing crane stability is the physical fitness of the crane operator (B4.7). The ergonomic design of the crane cab, encompassing the driver's seat and related components, plays a vital role in determining the visibility and posture of the crane operator. Zunjic et al. (2015) emphasize the need to reassess traditional crane cabin designs to align with human body characteristics, ensuring that they meet the operational needs of crane operators effectively. Swuste (2013) highlights that crane design and manufacturing are pivotal factors contributing to accidents, underscoring that these aspects should not be overlooked in safety considerations.

6. Recommendations

Given the findings of this study, five recommendations are suggested from the FG meeting to reduce the risks of mobile cranes on construction sites, considering the identified top ten critical risk factors.

6.1. Foster bidirectional communication during pre-lifting, lifting, and post-lifting activities

Effective communication should occur through dual channels, as emphasized by Lingard et al. (2014), who noted that the quality of communication would moderate the quality of risk control outcomes. Communication in lifting operations can be categorized into two major aspects. Before the lifting activities commence, all relevant site management, frontline supervisors, and lifting operation workers should get involved in preparing or reviewing the lifting plan, workshop, and daily or pre-work briefing sessions. The facilitator of these meetings plays a crucial role in leading discussions, encouraging participants to express their understanding, share concerns, and provide suggestions. This inclusive approach fosters a collaborative environment that enhances the viability and implement ability of the lifting plan, particularly in light of unique site conditions.

During the lifting operation, it is essential to establish a clear lifting system, such as the "3, 3, 3" method, which involves lifting from the ground to a height of 30 cm and maintaining a distance of at least 3 meters between lifting operators and the lifting object. Effective hand signals and communication devices should be well-prepared and understood by all frontline supervisors and workers. One of the FG members mentioned that many construction sites in Hong Kong utilize walkie-talkies for communication during lifting operations. The presence of multiple channels, often exceeding ten, can lead to communication interference, undermining effectiveness. Therefore, adopting new technologies or enhancing communication channels is vital to ensure clear and reliable communication throughout the lifting process.

6.2. Provide targeted lifting-related training for various stakeholders, including high-risk trades

The analysis of the questionnaire results indicates that working experience, knowledge, and training significantly enhance risk perception among personnel. Effective training is essential for minimizing human-related crane failures, as it equips personnel with the necessary skills to select and utilize lifting appliances and gear correctly (Neitzel et al., 2001). Training should aim to shift workers' mindsets towards adopting more scientific and systematic approaches in their work and decision-making processes. The design and development of safety training programs can draw upon the findings of Loosemore and Malouf (2019), who emphasize that effective safety training not only develops technical skills but also fosters flexibility, responsiveness, and interactivity, thereby enhancing workers' awareness of safety. Besides the classroom lecture, innovative training methods should be employed. Teizer et al. (2013) and Sadeghi et al. (2021) suggest using a game engine to create 3D environments for safety training, providing a realistic training experience that immerses participants in simulated scenarios. Moreover, simultaneous work activities should be minimized whenever possible. Task-specific risk assessments and detailed methodological instructions should be implemented to address potential hazards. Previous studies support these recommendations; for instance, Beavers et al. (2006) noted that workers who frequently operate near cranes should receive crane-related safety training before engaging in such activities, which enhances their risk perception and overall safety awareness. By investing in comprehensive training programs tailored to the needs of different stakeholders, construction sites can significantly reduce risks associated with mobile crane operations.

6.3. Promote a positive safety attitude and commitment among main contractors

The safety attitude of the main contractor is identified as one of the top ten critical factors affecting mobile crane safety. This finding aligns with prior research, where Qayoom and Hadikusumo (2019) and Wang et al. (2016) demonstrated that the behaviour and attitude of top management towards safety significantly impact workers' risk tolerance. When safety regulations are integrated into in-house rules established by main contractors, encompassing mandatory supervision, monitoring, and stringent penalties for unsafe actions, workers typically exhibit lower safety risk tolerance (Wang et al., 2016). To enhance safety leadership, insights from Stiles et al. (2018) can be applied. They advocate for improving safety leadership by increasing visibility regarding safety concerns, promoting workforce involvement, recognizing exemplary safety performance, and ensuring effective communication throughout the project. Most of the FG members have expressed that in Hong Kong, many construction projects face tight deadlines, which often lead main contractors to prioritize schedule adherence over safety. This pressure to "sacrifice safety" to meet construction timelines represents a significant challenge. Consequently, the reasonableness of the construction period emerges as a fundamental issue affecting the safety attitudes of main contractors. By addressing these challenges and fostering a culture that prioritizes safety alongside project timelines, main contractors can significantly improve mobile crane safety outcomes on construction sites. This commitment not only protects workers but also enhances overall project performance and sustainability.

6.4. Ensure competent and physical fitness of all lifting-related operators and workers

Five of the top ten critical factors affecting mobile crane safety are related to lifting workers, including crane operators, signalers, and riggers. A notable concern is that these lifting-related operators often rely heavily on their previous working experience and established trade practices. This observation is supported by Low et al. (2019), who found that cognitive biases among construction workers lead to mental shortcuts in judgment, characterized by overconfidence, an illusion of control, and a belief in their capabilities. Such cognitive biases can result in riskier behaviors. To mitigate these risks, Thevendran and Mawdesley (2004) suggested that focusing on human factors may enhance practitioners' awareness of these risks. FG members concurred that in actual construction, competency in lifting tasks may not always correlate with prior experience or training. Companies typically conduct random assessments of crane operators, riggers, and signalers during lifting tasks. If an assessment reveals unsatisfactory performance, the worker is required to undergo specialized, tailored training aimed at enhancing their knowledge and altering unsafe behaviors before they can undertake new lifting tasks.

Additionally, the physical and mental health of crane operators is critical for safety. Innovative technologies and monitoring measures can assist in addressing operator fatigue. Liu et al. (2021) investigated methods to detect crane operator fatigue, which could contribute to creating a comprehensive fatigue dataset for these workers. Technologies and monitoring systems, approved under the Construction Innovation and Technology Funding (CITF), can utilize facial recognition to monitor operators for signs of drowsiness. This system can provide audible and vibrating alerts when fatigue or unsafe operation behavior is detected, thereby enhancing safety during crane operations. By ensuring all lifting-related operators are both competent and physically fit, construction sites can significantly reduce the risks associated with mobile crane operations.

6.5. Regularly update the regulations and safety standards of mobile cranes

The safety inputs, inspections, and checks conducted by crane subcontractors, along with the reliability of crane structural parts, are among the top ten critical factors impacting mobile crane safety in Hong Kong. Therefore, the involvement and input from crane subcontractors are essential and should not be overlooked. FG members have raised two key issues regarding mobile crane safety that warrant attention. First, the Labor Department must collaborate closely with crane suppliers to conduct periodic reviews of existing regulations. This collaboration is vital to ensure that regulations and requirements are updated in line with the latest technologies incorporated in new mobile crane models. The second issue pertains to the assembly of lorry-mounted cranes. The relevant government authorities must review current regulations and provide clear guidance to both crane suppliers and bodybuilders regarding the requirements for crane assembly. Additionally, a comprehensive checking and inspection procedure is necessary to confirm that the crane's functionality, performance, stability, and load chart comply with the manufacturer's specifications. By regularly updating regulations and safety standards, the safety framework governing mobile crane operations can remain robust and responsive to evolving technologies and practices, ultimately enhancing safety on construction sites.

7. Conclusions

This study has systematically investigated the risk perception and safety concerns associated with mobile crane operations in Hong Kong, identifying key factors affecting mobile crane safety through a rigorous questionnaire survey. Rasmussen's risk management framework was employed to organize the risk factors associated with mobile cranes in Hong Kong. Based on 509 valid responses, SI analysis was utilized to rank the critical risk factors. The following top critical factors were identified: 1) Communication during lifting operations; 2) Crane operator safety awareness and operation; 3) Main contractor safety awareness and operation; 4) Rigger safety awareness and direction; 5) Crane subcontractor safety plans and working environment concerns; 6) Crane operator physical and mental health; 7) Signaller safety awareness and direction; 8) Crane operator routine checks; 9) Reliability of crane structural parts and ergonomics; 10) Crane subcontractor safety inspections and maintenance; and 11) Main contractor safety management and input. These findings contribute significantly to safety theory by providing a structured, empirically validated risk hierarchy within the Rasmussen framework, enriching the body of knowledge on human-technical-organizational interactions in high-risk construction activities.

A focus group meeting among 11 senior experts was conducted to analyse the influencing mechanisms of these factors and provide corresponding five practical recommendations, including 1) foster bidirectional communication during pre-lifting, lifting and post-lifting activities; 2) provide targeted lifting-related training for various stakeholders, including high-risk trades; 3) promote a positive safety attitude and commitment among main contractors; 4) ensure competent and physical fitness of all lifting-related operators and workers; 5) regularly update the regulations and safety standards of mobile cranes. By implementing these recommendations, stakeholders can enhance mobile crane safety and significantly reduce the risk of accidents, thereby protecting both workers and the public in Hong Kong's dynamic construction environment. These recommendations offer actionable guidance for industry practitioners to develop systematic safety interventions, thereby enhancing operational reliability and project outcomes. Regarding transferability, we acknowledge that the specific SI rankings and the dominance of certain factors (e.g., spatial communication issues) are heavily influenced by Hong Kong's unique regulatory and spatial context. However, the study provides a robust methodological blueprint for other high-density cities. Policymakers and companies in similar urban contexts can adopt the Rasmussen-based framework and mixed-methods approach to systematically identify and prioritize their own critical risk factors, thereby designing context-specific safety protocols and training programs.

However, several limitations should be acknowledged. First, while the inclusion of four key on-site stakeholder groups (site management, safety practitioners, operators, and general workers) provided a robust operational perspective, the views of other influential parties, such as project clients, government regulators, and design consultants, were not captured. Second, the contextual focus on Hong Kong, while providing depth and specificity to the findings, necessitates caution regarding direct generalizability to other regions with differing regulatory frameworks, labour markets, or construction methodologies. This context-specificity, however, presents a valuable opportunity for future comparative research. Conducting parallel studies in other high-density urban environments or contrasting regions would help disentangle universal risk factors from locally contingent ones, thereby enriching the theoretical model of mobile crane safety. Third, the study relied on perceptual measures of risk severity. Future research could track how risk perceptions and safety outcomes evolve with the implementation of specific interventions, such as new technologies or training programs. Additionally, integrating objective safety performance data (e.g., near-miss reports, incident rates) with perceptual surveys would strengthen the validity of the findings and provide a more comprehensive assessment of safety management effectiveness.

Funding

This study was not directly funded.

Author contributions

Angela Yuen conceived the study, designed the data analysis framework, and wrote the first draft of the article. Wen Yi supervised this study and contributed to the study's design. Rongyan Li was responsible for manuscript revision and figure preparation. Albert Chan and Yang Yang provided critical guidance in formulating the research methodology, guided the data analysis, and supervised the overall scientific direction. Hung-Lin Chi contributed to manuscript revision and logical flow enhancement.

Disclosure statement

The authors have reported no potential conflicts of interest.

Data availability statement

Data will be made available on request.

References

Afshari, D., Mazloumi, A., Nourollahi-Darabad, M., Saraji, G. N., & Foroushani, A. R. (2021). Effect of neck posture on cervicothoracic loads in overhead crane operators. *International Journal of Occupational Safety and Ergonomics*, *27*(1), 316–322. https://doi.org/10.1080/10803548.2018.1458436

Al Qudah, S. M. A., Fuentes-Bargues, J. L., & Ferrer-Gisbert, P. S. (2024). Bibliometric analysis of the literature on risk management in the construction sector: Exploring current and future trends. *Ain Shams Engineering Journal*, *15*(8), Article 102843. https://doi.org/10.1016/j.asej.2024.102843

Al-Humaidi, H. M., & Tan, F. H. (2009). Mobile crane safe operation approach to prevent electrocution using fuzzy-set logic models. *Advances in Engineering Software*, *40*(8), 686–696. https://doi.org/10.1016/j.advengsoft.2008.11.016

An, S. H. (2022). Analysis of factors behind human error in fatal construction accidents using the m-SHEL model. *Journal of the Korea Institute of Building Construction*, *22*(4), 415–423.

An, J., Wu, M., She, J., & Terano, T. (2018). Re-optimization strategy for truck crane lift-path planning. *Automation in Construction*, *90*, 146–155. https://doi.org/10.1016/j.autcon.2018.02.029

Araya, H., Kakuzen, M., Kinugawa, H., & Arai, T. (2004). Level luffing control system for crawler cranes. *Automation in Construction*, *13*(5), 689–697. https://doi.org/10.1016/j.autcon.2004.04.011

Beavers, J. E., Moore, J. R., Rinehart, R., & Schriver, W. R. (2006). Crane-related fatalities in the construction industry. *Journal of Construction Engineering and Management*, *132*(9), 901–910. https://doi.org/10.1061/(ASCE)0733-9364(2006)132:9(901)

Chae, S., & Yoshida, T. (2010). Application of RFID technology to prevention of collision accident with heavy equipment. *Automation in Construction*, *19*(3), 368–374. https://doi.org/10.1016/j.autcon.2009.12.008

Chan, A. P., Wong, F. K., Hon, C. K., & Choi, T. N. (2018). A Bayesian network model for reducing accident rates of electrical and mechanical (E&M) work. *International Journal of Environmental Research and Public Health*, *15*(11), Article 2496. https://doi.org/10.3390/ijerph15112496

Chen, Y., Okudan, G. E., & Riley, D. R. (2010). Sustainable performance criteria for construction method selection in concrete buildings. *Automation in Construction*, *19*(2), 235–244. https://doi.org/10.1016/j.autcon.2009.10.004

Chen, J., Fang, Y., & Cho, Y. K. (2017). Real-time 3D crane workspace update using a hybrid visualization approach. *Journal of Computing in Civil Engineering*, *31*(5), Article 04017049. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000698

El-Sayegh, S. M., & Mansour, M. H. (2015). Risk assessment and allocation in highway construction projects in the UAE. *Journal of Management in Engineering*, *31*(6), Article 04015004. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000365

Esmaeili, R., Ali Babaei, A., & Monazami Tehrani, G. (2021). Relationship between safety investment and safety performance indices considering the project hazard level in construction industry. *Journal of Health and Safety at Work*, *11*(2), 327–352.

Fang, Y., & Cho, Y. K. (2017). Effectiveness analysis from a cognitive perspective for a real-time safety assistance system for mobile crane lifting operations. *Journal of Construction Engineering and Management*, *143*(4), Article 05016025. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001258

Fang, Y., Cho, Y. K., & Chen, J. (2016). A framework for real-time pro-active safety assistance for mobile crane lifting operations. *Automation in Construction*, *72*, 367–379. https://doi.org/10.1016/j.autcon.2016.08.025

Feng, Y. (2013). Effect of safety investments on safety performance of building projects. *Safety Science*, *59*, 28–45. https://doi.org/10.1016/j.ssci.2013.04.004

Feng, Q., Wang, K., Feng, Y., Shi, X., Rao, Y., & Wei, J. (2023). Incentives for promoting safety in the Chinese construction industry. *Buildings*, *13*(6), Article 1446. https://doi.org/10.3390/buildings13061446

Galindo, J. G., Vazquez, J. E., Fox, C., & Desplain, O. (2013, June). Improvement in mechanical lifting safety performance through a supervisor training program. In *SPE Latin American and Caribbean Health*, *Safety*, *Environment*, *and Sustainability Symposium* (Article SPE-165643), Lima, Peru. SPE. https://doi.org/10.2118/165643-MS

Gelo, O., Braakmann, D., & Benetka, G. (2008). Quantitative and qualitative research: Beyond the debate. *Integrative Psychological and Behavioral Science*, *42*(3), 266–290. https://doi.org/10.1007/s12124-008-9078-3

George, D., & Mallery, P. (2024). *IBM SPSS Statistics 29 step by step*: *A simple guide and reference* (18th ed.). Routledge. https://doi.org/10.4324/9781032622156

Goncalves Filho, A. P., Waterson, P., & Jun, G. T. (2021). Improving accident analysis in construction–Development of a contributing factor classification framework and evaluation of its validity and reliability. *Safety Science*, *140*, Article 105303. https://doi.org/10.1016/j.ssci.2021.105303

Guo, B. H., Goh, Y. M., & Wong, K. L. X. (2018). A system dynamics view of a behavior-based safety program in the construction industry. *Safety Science*, *104*, 202–215. https://doi.org/10.1016/j.ssci.2018.01.014

Guo, H., Zhou, Y., Pan, Z., Zhang, Z., Yu, Y., & Li, Y. (2022). Automated selection and localization of mobile cranes in construction planning. *Buildings*, *12*(5), Article 580. https://doi.org/10.3390/buildings12050580

Hair, J. F., Babin, B. J., Anderson, R. E., & Black, W. C. (2019). *Multivariate data analysis* (8th ed.). England Pearson Prentice.

Hamid, A. R. A., Azhari, R., Zakaria, R., Aminudin, E., Jaya, R. P., Nagarajan, L., & Yunus, R. (2019). Causes of crane accidents at construction sites in Malaysia. *IOP Conference Series*: *Earth and Environmental Science*, *220*, Article 012028. https://doi.org/10.1088/1755-1315/220/1/012028

Han, S., Bouferguene, A., Al-Hussein, M., & Hermann, U. (2017). 3D-based crane evaluation system for mobile crane operation selection on modular-based heavy construction sites. *Journal of Construction Engineering and Management*, *143*(9), Article 04017060. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001360

Han, S. H., Hasan, S., Bouferguène, A., Al-Hussein, M., & Kosa, J. (2015). Utilization of 3D visualization of mobile crane operations for modular construction on-site assembly. *Journal of Management in Engineering*, *31*(5), Article 04014080. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000317

Han, S., Hasan, S., Bouferguene, A., Al-Hussein, M., & Kosa, J. (2018). An integrated decision support model for selecting the most feasible crane at heavy construction sites. *Automation in Construction*, *87*, 188–200. https://doi.org/10.1016/j.autcon.2017.12.009

He, W., Lin, Z., Li, W., Wong, C. J., Kong, D., & Loh, W. E. (2025). The comprehensive safety assessment method for complex construction crane accidents based on scenario analysis – A case study of crane accidents. *Computers & Industrial Engineering*, *199*, Article 110716. https://doi.org/10.1016/j.cie.2024.110716

Hong Kong Labour Department. (2024). *Occupational safety and health statistics 2024*. https://www.housingauthority.gov.hk/mini-site/site-safety/common/resources/article/pdf/publications/performance-statistics/PDF/en_10.pdf

Hong Kong Labour Department. (2025). *Occupational safety and health*. https://www.labour.gov.hk/eng/osh/content10.htm

Hung, W. H., Liu, C. W., Liang, C. J., & Kang, S. C. (2016). Strategies to accelerate the computation of erection paths for construction cranes. *Automation in Construction*, *62*, 1–13. https://doi.org/10.1016/j.autcon.2015.10.008

Hwang, S. (2012). Ultra-wide band technology experiments for real-time prevention of tower crane collisions. *Automation in Construction*, *22*, 545–553. https://doi.org/10.1016/j.autcon.2011.11.015

Im, S., & Park, D. (2020). Crane safety standards: Problem analysis and safety assurance planning. *Safety Science*, *127*, Article 104686. https://doi.org/10.1016/j.ssci.2020.104686

Ji, Y., & Leite, F. (2018). Automated tower crane planning: Leveraging 4-dimensional BIM and rule-based checking. *Automation in Construction*, *93*, 78–90. https://doi.org/10.1016/j.autcon.2018.05.003

Kan, C., Fang, Y., Anumba, C. J., & Messner, J. I. (2018). A cyber–physical system (CPS) for planning and monitoring mobile cranes on construction sites. *Proceedings of the Institution of Civil Engineers-Management*, *Procurement and Law*, *171*(6), 240–250. https://doi.org/10.1680/jmapl.17.00042

Kargar, V., Jahangiri, M., Alimohammadlu, M., Kamalinia, M., & Mirazahossieninejad, M. (2022). Risk assessment of mobile crane overturning in Asymmetric Tandem Lifting (ATL) operation based on fuzzy fault tree analysis (FFTA). *Results in Engineering*, *16*, Article 100755. https://doi.org/10.1016/j.rineng.2022.100755

Kim, S., & Kang, C. (2022). Analysis of the complex causes of death accidents due to mobile cranes using a modified MEPS method: Focusing on South Korea. *Sustainability*, 14(5), Article 2948. https://doi.org/10.3390/su14052948

King, R. A. (2012). *Analysis of crane and lifting accidents in North America from 2004 to 2010* [Doctoral dissertation]. Massachusetts Institute of Technology. http://hdl.handle.net/1721.1/73792

Krueger, R. A. (2014). *Focus groups*: *A practical guide for applied research*. Sage publications.

Lai, K. C., & Kang, S. C. (2009). Collision detection strategies for virtual construction simulation. *Automation in Construction*, *18*(6), 724–736. https://doi.org/10.1016/j.autcon.2009.02.006

Lee, Y., & Jung, K. (2022). Analysis of perceived accident causes and special training status for safety of crane operation. *Journal of the Korea Safety Management & Science*, *24*(1), 91–98. https://doi.org/10.12812/ksms.2022.24.1.091

Lee, C. K., & Foo, M. Y. (2022). Risk attitudes and the big five personality traits: A study on construction project practitioners in Malaysia. *International Journal of Construction Management*, *22*(13), 2435–2445. https://doi.org/10.1080/15623599.2020.1793506

Lee, J., Phillips, I., & Lynch, Z. (2022). Causes and prevention of mobile crane-related accidents in South Korea. *International Journal of Occupational Safety and Ergonomics*, *28*(1), 469–478. https://doi.org/10.1080/10803548.2020.1775384

Li, R., Chi, H. L., Peng, Z., Li, X., & Chan, A. P. (2023). Automatic tower crane layout planning system for high-rise building construction using generative adversarial network. *Advanced Engineering Informatics*, *58*, Article 102202. https://doi.org/10.1016/j.aei.2023.102202

Li, R., Hung-Lin, C. H. I., Hu, Z., Li, D., Yi, W., & Brilakis, I. (2025). Data-driven lifting-centered construction site layout planning decision approach with BIM. *Automation in Construction*, *179*, Article 106467. https://doi.org/10.1016/j.autcon.2025.106467

Li, Y., & Liu, C. (2012). Integrating field data and 3D simulation for tower crane activity monitoring and alarming. *Automation in Construction*, *27*, 111–119. https://doi.org/10.1016/j.autcon.2012.05.003

Lingard, H., Pirzadeh, P., Blismas, N., Wakefield, R., & Kleiner, B. (2014). Exploring the link between early constructor involvement in project decision-making and the efficacy of health and safety risk control. *Construction Management and Economics*, *32*(9), 918–931. https://doi.org/10.1080/01446193.2014.911931

Liu, P., Chi, H. L., Li, X., & Guo, J. (2021). Effects of dataset characteristics on the performance of fatigue detection for crane operators using hybrid deep neural networks. *Automation in Construction*, *132*, Article 103901. https://doi.org/10.1016/j.autcon.2021.103901

Liu, J., Wang, X., Nie, X., & Lu, R. (2022). Incentive mechanism of construction safety from the perspective of mutual benefit. *Buildings*, *12*(5), Article 536. https://doi.org/10.3390/buildings12050536

Loosemore, M., & Malouf, N. (2019). Safety training and positive safety attitude formation in the Australian construction industry. *Safety Science*, *113*, 233–243. https://doi.org/10.1016/j.ssci.2018.11.029

Low, B. K. L., Man, S. S., Chan, A. H. S., & Alabdulkarim, S. (2019). Construction worker risk-taking behavior model with individual and organizational factors. *International Journal of Environmental Research and Public Health*, *16*(8), Article 1335. https://doi.org/10.3390/ijerph16081335

Man, S. S., Ng, J. Y. K., & Chan, A. H. S. (2019). A review of the risk perception of construction workers in construction safety. In T. Ahram, W. Karwowski, S. Pickl, & R. Taiar (Eds.), *Advances in intelligent systems and computing*: *Vol. 1026*. *Human systems engineering and design II. IHSED 2019* (pp. 637–643). Springer, Cham. https://doi.org/10.1007/978-3-030-27928-8_97

Mansoor, A., Liu, S., Ali, G. M., Bouferguene, A., & Al-Hussein, M. (2020). Conceptual framework for safety improvement in mobile cranes. In *Construction Research Congress 2020* (pp. 964–971). American Society of Civil Engineers. https://doi.org/10.1061/9780784482865.102

Milazzo, M. F., Ancione, G., Brkić, V. S., & Vališ, D. (2017). Investigation of crane operation safety by analysing main accident causes. In *Risk*, *reliability and safety*: *Innovating theory and practice* (pp. 74–80). CRC Press-Taylor & Francis Group.

Mohammadi, H., Fazli, Z., Kaleh, H., Azimi, H. R., Moradi Hanifi, S., & Shafiee, N. (2021). Risk analysis and reliability assessment of overhead cranes using fault tree analysis integrated with Markov chain and fuzzy Bayesian networks. *Mathematical Problems in Engineering*, *2021*, Article 6530541. https://doi.org/10.1155/2021/6530541

Neitzel, R. L., Seixas, N. S., & Ren, K. K. (2001). A review of crane safety in the construction industry. *Applied Occupational and Environmental Hygiene*, *16*(12), 1106–1117. https://doi.org/10.1080/10473220127411

Nketekete, M., Emuze, F., & Smallwood, J. (2016). Risk management in public sector construction projects: Case studies in Lesotho. *Acta Structilia*, *23*(2), 1–24. https://doi.org/10.18820/24150487/as23i2.1

Obondi, K. (2022). The utilization of project risk monitoring and control practices and their relationship with project success in construction projects. *Journal of Project Management*, *7*(1), 35–52. https://doi.org/10.5267/j.jpm.2021.7.002

Othman, I., Kineber, A. F., Oke, A. E., Zayed, T., & Buniya, M. K. (2021). Barriers of value management implementation for building projects in Egyptian construction industry. *Ain Shams Engineering Journal*, *12*(1), 21–30. https://doi.org/10.1016/j.asej.2020.08.004

Qayoom, A., & Hadikusumo, B. H. W. (2019). Multilevel safety culture affecting organization safety performance: A system dynamic approach. *Engineering*, *Construction and Architectural Management*, *26*(10), 2326–2346. https://doi.org/10.1108/ECAM-08-2018-0355

Rasmussen, J. (1997). Risk management in a dynamic society: A modelling problem. *Safety Science*, *27*(2–3), 183–213. https://doi.org/10.1016/S0925-7535(97)00052-0

Raviv, G., & Shapira, A. (2018). Systematic approach to crane-related near-miss analysis in the construction industry. *International Journal of Construction Management*, *18*(4), 310–320. https://doi.org/10.1080/15623599.2017.1382067

Raviv, G., Fishbain, B., & Shapira, A. (2017). Analyzing risk factors in crane-related near-miss and accident reports. *Safety Science*, *91*, 192–205. https://doi.org/10.1016/j.ssci.2016.08.022

Romanello, G. (2018). Stability analysis of mobile cranes and determination of outriggers loading. *Journal of Engineering*, *Design and Technology*, *16*(6), 938–958. https://doi.org/10.1108/JEDT-05-2018-0084

Romanello, G. (2022). A graphical approach for the determination of outrigger loads in mobile cranes. *Mechanics Based Design of Structures and Machines*, *50*(3), 767–780. https://doi.org/10.1080/15397734.2020.1726184

Sadeghi, S., Soltanmohammadlou, N., & Rahnamayiezekavat, P. (2021). A systematic review of scholarly works addressing crane safety requirements. *Safety Science*, *133*, Article 105002. https://doi.org/10.1016/j.ssci.2020.105002

Sankar, S. S., Anandh, K. S., & Prasanna, K. (2024). Safety leadership: A catalyst for positive safety climate on construction sites. *Buildings*, *14*(6), Article 1806. https://doi.org/10.3390/buildings14061806

Schuldt, S. J., Nicholson, M. R., Adams, Y. A., II, & Delorit, J. D. (2021). Weather-related construction delays in a changing climate: A systematic state-of-the-art review. *Sustainability*, *13*(5), Article 2861. https://doi.org/10.3390/su13052861

Sertyesilisik, B., Tunstall, A., & McLoughlin, J. (2010). An investigation of lifting operations on UK construction sites. *Safety Science*, *48*(1), 72–79. https://doi.org/10.1016/j.ssci.2009.06.001

Shannon, H. S., Mayr, J., & Haines, T. (1997). Overview of the relationship between organizational and workplace factors and injury rates. *Safety Science*, *26*(3), 201–217. https://doi.org/10.1016/S0925-7535(97)00043-X

Shapira, A., Lucko, G., & Schexnayder, C. J. (2007). Cranes for building construction projects. *Journal of Construction Engineering and Management*, *133*(9), 690–700. https://doi.org/10.1061/(ASCE)0733-9364(2007)133:9(690)

Shi, Y., Yang, J., & Wen, Y. (2019). Research on the construction of safety risk management objective system based on causes-means. In *International Academic Conference on Frontiers in Social Sciences and Management Innovation* (*IAFSM 2018*) (pp. 56–61). Atlantis Press. https://doi.org/10.2991/iafsm-18.2019.9

Shringi, A., Arashpour, M., Golafshani, E. M., Rajabifard, A., Dwyer, T., & Li, H. (2022). Efficiency of VR-based safety training for construction equipment: Hazard recognition in heavy machinery operations. *Buildings*, *12*(12), Article 2084. https://doi.org/10.3390/buildings12122084

Sitompul, T. A., Lindell, R., Wallmyr, M., & Siren, A. (2020). Presenting information closer to mobile crane operators' line of sight: Designing and evaluating visualization concepts based on transparent displays. In *Graphics Interface 2020* (Article 59).

Šopić, M., Vranković, A., & Marović, I. (2025). Understanding and quantifying the impact of adverse weather on construction productivity. *Applied Sciences*, *15*(19), Article 10759. https://doi.org/10.3390/app151910759

Spasojević Brkić, V. K., Veljković, Z. A., Golubović, T., Brkić, A. D., & Kosić Šotić, I. (2016). Workspace design for crane cabins applying a combined traditional approach and the Taguchi method for design of experiments. *International Journal of Occupational Safety and Ergonomics*, *22*(2), 228–240. https://doi.org/10.1080/10803548.2015.1111713

Sruthy, S., & Xavier, A. S. (2023). A study on crane accidents: Investigating the role of hand signals in construction site communication. *Sustainability*, *Agri*, *Food and Environmental Research*. https://doi.org/10.7770/safer-V12N-art787

Stiles, S., Ryan, B., & Golightly, D. (2018). Evaluating attitudes to safety leadership within rail construction projects. *Safety Science*, *110*, 134–144. https://doi.org/10.1016/j.ssci.2017.12.030

Sun, Y., Fang, D., Wang, S., Dai, M., & Lv, X. (2008). Safety risk identification and assessment for Beijing Olympic venues construction. *Journal of Management in Engineering*, *24*(1), 40–47. https://doi.org/10.1061/(ASCE)0742-597X(2008)24:1(40)

Sun, Z., Hou, N., & Xiang, H. (2009). Safety and serviceability assessment for high-rise tower crane to turbulent winds. *Frontiers of Architecture and Civil Engineering in China*, *3*(1), 18–24. https://doi.org/10.1007/s11709-009-0009-2

Swuste, P. (2013). A 'normal accident' with a tower crane? An accident analysis conducted by the Dutch Safety Board. *Safety Science*, *57*, 276–282. https://doi.org/10.1016/j.ssci.2013.03.002

Taghaddos, H., Eslami, A., Hermann, U., AbouRizk, S., & Mohamed, Y. (2019). Auction-based simulation for industrial crane operations. *Automation in Construction*, *104*, 107–119. https://doi.org/10.1016/j.autcon.2019.03.015

Tam, V. W., & Fung, I. W. (2011). Tower crane safety in the construction industry: A Hong Kong study. *Safety Science*, *49*(2), 208–215. https://doi.org/10.1016/j.ssci.2010.08.001

Teizer, J., Cheng, T., & Fang, Y. (2013). Location tracking and data visualization technology to advance construction ironworkers' education and training in safety and productivity. *Automation in Construction*, *35*, 53–68. https://doi.org/10.1016/j.autcon.2013.03.004

Thevendran, V., & Mawdesley, M. J. (2004). Perception of human risk factors in construction projects: An exploratory study. *International Journal of Project Management*, *22*(2), 131–137. https://doi.org/10.1016/S0263-7863(03)00063-2

Trethewy, R. W., Atkinson, M., & Falls, B. (2003). Improved hazard identification for contractors in the construction industry. *Journal of Construction Research*, *4*, 71–85. https://doi.org/10.1142/S1609945103000315

U.S. Bureau of Labor Statistics. (2024). *Census of fatal occupational injuries* (News release). https://www.bls.gov/news.release/archives/cfoi_12192024.htm

Wang, H., Kamal, E. M., & Ulang, N. M. (2024). Supervisor leadership and construction worker safety behavior: A systematic literature review. *Journal of Southwest Jiaotong University*, *59*(2), Article 33. https://doi.org/10.35741/issn.0258-2724.59.2.33

Wang, T., Tang, W., Du, L., Duffield, C. F., & Wei, Y. (2016). Relationships among risk management, partnering, and contractor capability in international EPC project delivery. *Journal of Management in Engineering*, *32*(6), Article 04016017. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000459

Wu, C., Wang, F., Zou, P. X. W., & Fang, D. (2016). How safety leadership works among owners, contractors and subcontractors in construction projects. *International Journal of Project Management*, *34*(5), 789–805. https://doi.org/10.1016/j.ijproman.2016.02.013

Wu, X., Qian, Q., & Zhang, M. (2024a). Impact of supervisor leadership on construction worker safety behavior in China: The moderating role of social capital. *Engineering, Construction and Architectural Management*, *31*(5), 1947–1972. https://doi.org/10.1108/ECAM-02-2022-0180

Wu, B. J., Jin, L. H., Zheng, X. Z., & Chen, S. (2024b). Coupling analysis of crane accident risks based on Bayesian network and the NK model. *Scientific Reports*, *14*(1), Article 1133. https://doi.org/10.1038/s41598-024-51425-9

Xu, Z., Zayed, T., & Niu, Y. (2020). Comparative analysis of modular construction practices in mainland China, Hong Kong and Singapore. *Journal of Cleaner Production*, *245*, Article 118861. https://doi.org/10.1016/j.jclepro.2019.118861

Yang, Y., Chan, A. P. C., Darko, A., Gao, R., & Zahoor, H. (2019). Factors affecting structural steelwork adoption from a project lifecycle perspective: The case of Hong Kong. *Journal of Cleaner Production*, *230*, 634–646. https://doi.org/10.1016/j.jclepro.2019.05.123

Zhang, R. P., Lingard, H., & Oswald, D. (2020). Impact of supervisory safety communication on safety climate and behavior in construction workgroups. *Journal of Construction Engineering and Management*, *146*(8), Article 04020089. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001881

Zhong, H., Chen, L., Antwi-Afari, M. F., Bao, Z., & Chen, K. (2025). Dynamic risk assessment of tower crane operations by integrating functional resonance analysis method and Bayesian network. *Developments in the Built Environment*, *23*, Article 100699. https://doi.org/10.1016/j.dibe.2025.100699

Zhang, C., & Hammad, A. (2012). Multiagent approach for realtime collision avoidance and path replanning for cranes. *Journal of Computing in Civil Engineering*, *26*(6), 782–794. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000181

Zhou, W., Zhao, T., Liu, W., & Tang, J. (2018). Tower crane safety on construction sites: A complex sociotechnical system perspective. *Safety Science*, *109*, 95–108. https://doi.org/10.1016/j.ssci.2018.05.001

Zunjic, A., Brkic, V. S., Klarin, M., Brkic, A., & Krstic, D. (2015). Anthropometric assessment of crane cabins and recommendations for design: A case study. *Work*, *52*(1), 185–194. https://doi.org/10.3233/WOR-152042