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Systematic review of the identification, assessment, and mitigation of safety risks in high-rise building construction

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Subject review

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Systematic review of the identification, assessment, and mitigation of safety risks in high-rise building construction

The construction industry accounts for a large proportion of the national GDP; however, it is one of the world's most dangerous industrial sectors. Existing studies have inadequately reviewed safety risk-related research in high-rise building construction. Therefore, this study conducts a systematic review of safety risks in high-rise building construction from 2004 to 2024. First, the paper presents investigates the causes of accidents and risk factors that endanger occupational safety and health, comprising 8 main factors and 60 sub-factors. Second, the paper explores the assessment methods for evaluating and ranking these safety risk factors, of which nine typical methods are elaborated. Finally, a technical framework for mitigating the eight main safety risk factors is established in paper, providing safety practitioners with access to cutting-edge technologies and methods in the construction industry. Furthermore, this study provides suggestions and future directions for addressing the drawbacks of current mitigation measures to sustainably improve building construction safety.

Key words:
construction industry, high-rise building, safety risk, identification, assessment, mitigation measures

Pregledni rad

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Sustavni pregled identifikacije, procjene i ublažavanja sigurnosnih rizika u visokogradnji

Građevinska industrija ima velik udio u nacionalnome BDP-u, no to je jedan od najopasnijih industrijskih sektora na svijetu. Postojeće su studije neadekvatno prikazale istraživanja vezana uz sigurnosne rizike u visokogradnji i zato ovo istraživanje nudi sustavni pregled rizika za život i zdravlje radnika u visokogradnji od 2004. do 2024. Prvo, istražuju se uzroci nesreća i čimbenici rizika koji ugrožavaju sigurnost i zdravlje na radu. Riječ je o osam glavnih čimbenika i 60 podčimbenika. Drugo, istražuju se metode procjene za ocjenjivanje i rangiranje tih čimbenika rizika, od kojih je razrađeno devet tipičnih metoda. Konačno, uspostavljen je tehnički okvir za ublažavanje osam glavnih čimbenika rizika za sigurnost čime je omogućeno stručnjacima za zaštitu na radu pristup najsuvremenijim tehnologijama i metodama u građevinskoj industriji. Također, ovo istraživanje nudi prijedloge i buduće smjernice za rješavanje nedostataka trenutačnih mjera ublažavanja kako bi se sigurnost u građevinarstvu održivo poboljšala.

Ključne riječi:
građevinska industrija, visokogradnja, sigurnosni rizik, identifikacija, procjena, mjere za ublažavanje

1. Introduction

Construction is one of the world's largest industrial sectors, accounting for a large proportion of the national gross domestic product (GDP), for example, 6.9 % in China [1] and 15.3 % in the UK [2]. In many developing countries, construction is among the fastest growing areas in the labour market. Although the construction industry makes a significant economic contribution to improving overall GDP, it is considered one of the world's most dangerous industrial sectors [3], accounting for 30 to 40 % of fatal injuries. In the U.S., according to the Bureau of Labor Statistics [5], the construction industry accounts for the second highest proportion (19.5 %) of workplace fatalities. Data from several industrialised countries show that construction workers are three to four times more likely to die from accidents than other workers. In the developing world, fatality risks may be three to six times greater [3].

Construction is increasingly focused on high-rise buildings owing to overcrowding in urban areas [7]. According to the National Fire Protection Association (NFPA), in the U.S., buildings higher than 23 m or seven floors are considered high-rise buildings [4]. According to the Uniform Standard for Civil Building Design (GB50352-2019), a high-rise building is defined as a building with a height greater than 27 m [8]. This paper adopts 27 m as the definition for a high-rise building. Safety refers to freedom from danger, harm, and injury to the person involved in construction activities. Traditionally, risk has been defined as a measure of the probability and severity of adverse effects. Mondarres et al. [9] defined risk as the probability of an event occurring and the magnitude of its consequences.

$$Risk = (S, P, C)$$

where S is Scenario leading to the hazard; P is Probability of occurrence; and C is Consequence (severity).

Afzan [10] summarised five main risk factors for high-rise buildings, namely "external motivation", "management motivation", "safety performance motivation", "workplace motivation" and "labor motivation". Lubega et al. [11] conducted a similar study that revealed that the causes of construction accidents in Uganda were a lack of knowledge about safety rules, engaging an inexperienced workforce, and a lack of respect for safety. Tam et al. [12] concurred with this opinion and suggested that the main factors influencing safety in China were managers' profound deficiencies in safety consciousness, a lack of safety training, reckless operations, and aversion to allocating resources to safety measures. Furthermore, a study conducted by Dejus [13] in the Lithuanian Republic identified that the primary causes of severe and fatal accidents stem from inexperienced personnel, insufficient qualifications, and a lack of awareness of risks at construction sites. Rahim et al. [14] conducted a survey in Malaysia aimed at identifying the factors contributing to accidents at construction sites and revealed that unsafe practices, encompassing erroneous procedures and levels of knowledge disregarding protocols, stand out as the most common cause of accidents at construction sites.

The construction of high-rise buildings is a complex process that involves multiple stakeholders, intricate engineering, and unique challenges. Safety risks are among the most important concerns in this context. However, in previous studies, safety risk-related research on high-rise building construction has been inadequate. Therefore, to fill this gap, this study conducted a systematic review of the construction safety risk identification, assessment, and mitigation of safety risks in high-rise building construction.

2. Research methodology

The research methodology was based on the verification of previous studies involving safety risk factors in the construction industry. This literature review encapsulates previous scholarly articles in the domain of safety concerning construction activities in high-rise building projects.

This study identified previous scholarly articles published between 2004 and 2024 (April) in the realm of safety within the context of high-rise building construction projects using a manual search in databases of papers. The databases encompassed Web of Science, Science Direct, and Scopus. The search string was formulated as ("safety" OR "accident" in subject terms) AND ("risk" OR "factor" OR "performance" in subject terms) AND ("high rise building*" OR "high-rise building*") AND ("construction" OR site in subject terms).

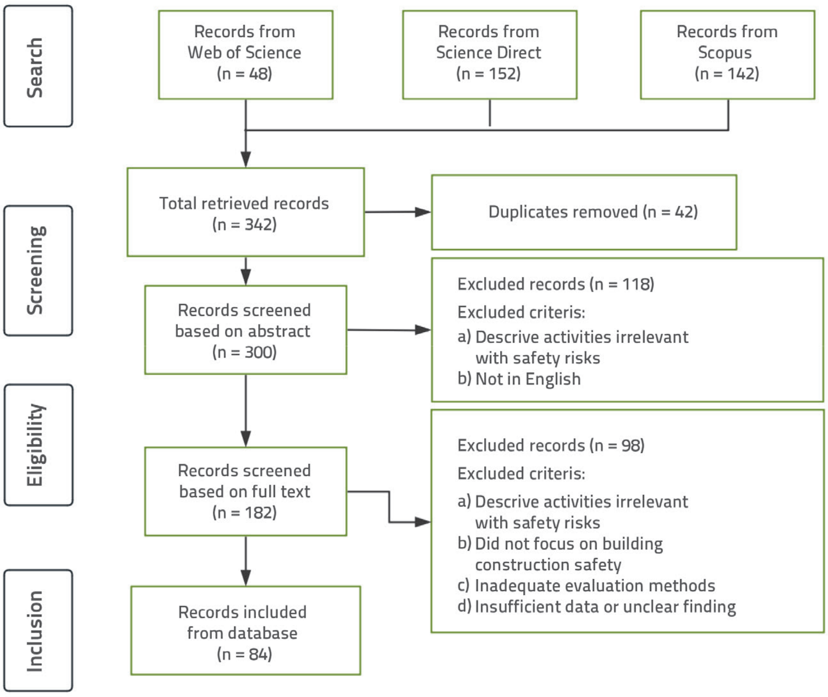


Figure 1. Research roadmap for the retrieval of research papers

The selected papers met the following criteria:

- they addressed the safety factors that contribute to accidents in high-rise building projects
- they were published between 2004 and 2024
- they were available online
- they were written in English. Ultimately, a total of 84 research papers were retrieved for the research.

Figure 1 shows the research roadmap for the retrieval of research papers**.**

The remainder of this paper is organised as follows: Section 3 provides an overview of the safety risk factors identified within the high-rise construction industry, including eight main safety risk factors. Section 4 outlines the methodologies used to assess and prioritise these safety risk factors. Section 5 describes the mitigation techniques for the eight main safety risk factors identified in Section 3. Section 6 presents the results and discussions.

3. Safety risk factors

This section elaborates and categorises eight main safety factors, including approximately 60 subfactors extracted from the literature, to explore the underlying causes of accidents at construction sites.

3.1. On-site temporary electricity factors

Li et al. [4] conducted a survey and found a significant latent safety hazard associated with temporary electrical usage at construction sites. Zhang et al. [15] pointed out that in response to the safety issues of temporary construction electricity, owing to poor management by construction enterprises, there is no special organisational design plan for construction electricity, or the plan is not reviewed by the supervision unit. This results in continuous hidden danger related to temporary electricity usage at construction sites, which can lead to significant casualties. In the UK, according to [16]. The number of fatalities caused by contact with electricity or electrical discharges during construction was 11, accounting for 23.9 % of that in the entire industry from 2019 to 2023. Luo [17] analysed the primary reasons for on-site electrical accidents, including workers' lack of electrical knowledge and the illegal use of electricity. The contributing factors include the absence of protective measures during high-voltage operations, workers not wearing proper PPE, and defective mechanical and electrical equipment, Table 1.

3.2. Fall from height factors

Within the realm of construction safety, there is a significant emphasis on addressing fatality and injury rates, particularly in high-rise building construction projects [18]. Hu et al. [19] found that among all construction accidents, falls from roofs or floors represent a significant cause of severe injuries (48 %) and fatalities (30 %). The most hazardous construction tasks in high-rise building projects involve working on roofs or floors [20]. Improper installation or the absence of secure fall protection are the two key immediate factors leading to fall accidents [21]. Additionally, Manzoor [22] found that "fall from roofs/floors" is identified as the most critical safety factor, followed closely by "personal protective equipment" (2022). The HSE revealed that 40 fatal injuries were due to falls from a height, accounting for 30 % of all worker deaths in 2023, and 54 % of all fatalities caused by falls from a height were in the construction sector [16]. HSE encompasses the policies, procedures, and practices that safeguard the well-being of workers, protect the environment, and ensure safe operations. The factor of falls from roofs or floors encompasses sub-factors such as inadequate roof edge protection measures, user ability failure, failure of safety net systems, and uncovered floor openings, Table 2.

Table 1.On-site temporary electricity safety factors

Br.	Safety risk factors	References
1	Worker's lack of electrical knowledge and use of electricity illegally	[4, 17]
2	No protective measures were taken for high-pressure offline operations	[17]
3	The workers did not wear proper PPE	[17]
4	The mechanical and electrical equipment is defective	[17]

Table 2. Fall from height factors

Br.	Safety risk factors	References
1	Lack of safety net system	[17, 22]
2	Inadequate roof edge protection measures	[17, 22]
3	Scaffolding failure/operating on hazardous scaffolding	[17, 22, 23]
4	Engaging in elevated tasks or near open edges without the implementation of fall-protection systems	[22]

Table 3. Safety inspection and safety warning sign

Br.	Safety risk factors	References
1	No daily records of safety checking	[22, 17, 23, 4]
2	Lack of regular safety meetings	[4, 17, 23, 27, 28, 29, 30, 31, 32]
3	Checking accidents without determining who was involved, when they occurred, or why/how they happened	[4, 22]
4	Failure to erect required signs	[22, 33]
5	No eye-catching cautionary signs	[22, 34]
6	Lack of on-site workers monitoring system	[22, 35, 36]
7	No workers location tracking system	[22, 36, 37]
8	Lack of potential safety hazards identification	[22]
9	Lack of night light warning sign	[23]
10	No site safety sign location plans	[22, 23]

Table 4. Personal protective equipment (PPE)

Br.	Safety risk factors	References
1	No safety equipment acquisition	[41, 42, 43, 44]
2	Workers not wearing personal protective equipment	[22, 38]
3	Negligence in the use of safety glasses and hearing protection	[45, 29, 22, 46, 47]
4	Negligence in the use of safety belts while working at heights	[48, 49, 22]
5	Negligence in wearing a safety helmet	[50, 22]

3.3. Safety inspection and safety warning sign factors

Safety inspections are considered significant for guaranteeing worker safety in construction and include daily safety checks, regular safety meetings, and detailed accident investigations, leading to the identification of who, when, and what/how [24, 25].

Eye-catching safety signs play an informing and warning role that affects construction safety. Safety signs are an important factor in preventing accidents during construction. Safety signs not only offer direction but also remind workers of potential hazards at construction sites [26]. In addition, Manzoor et al. [22] indicated that safety signs contain sub-factors such as a lack of safety sign location plans, failure to erect the required signs, the absence of warning signs, a lack of an on-site worker monitoring system, and no worker location tracking system, Table 3.

3.4. Personal protective equipment (PPE) factors

Personal protective equipment (PPE) is mentioned most frequently by researchers on construction safety. Temporary work during building projects is the main cause of accidents, resulting in severe injuries and fatalities. Workers who did not wear PPE were secondary reasons [38]. Even when safety managers provided PPE, the utilisation rate was low, particularly in moist and oppressive regions. Zuofa et al. [39] found that a significant number of construction workers refrained from using PPE because of feelings of discomfort. Moreover, the equipment is typically not worn properly. Therefore, it is essential to provide qualified PPE and ensure its proper utilisation [40], Table 4.

3.5. Unsafe work environment factors

At a construction site, workers are exposed to hazardous situations. An unsafe work environment involves sub-factors such as dusty and noisy conditions, cold or hot working places, severe wind working conditions, and fire hazards. Fire hazards in high-rise building construction, which may be uncommon, should also be regarded as a foremost safety concern because they lead to significant damage [51]. Weather conditions in some countries, such as China, are hot and torrid in summer, and severely cold in northern China in winter. It is difficult to work effectively on sites that are tolerant to poor working environment conditions, Table 5.

3.6. Personal factors and low knowledge and skill levels of workers

Workers' misbehaviour, motivation, bad temper, personal safety unawareness, personal competency, and lack of experience are sub-factors of personal factors. Motivation plays a crucial role in enhancing construction productivity. Research has shown that job satisfaction significantly influences the attitudes of construction workers [52]. Therefore, it is imperative for

Table 5. Unsafe work environment

Br.	Safety risk factors	References
1	Exposure to hazardous situation	[37, 32, 4]
2	Fire hazard	[22, 17, 23]
3	Dusty & noisy condition	[22, 4]
4	Cold or hot weather	[4, 17, 22, 23]
5	Severe windy condition	[4, 17, 22, 23]
6	Occupational health and safety conditions for site-resident workers	[22, 35]

Table 6. Personal factors and low knowledge & skill level of workers

Br.	Safety risk factors	References
1	Human error	[17, 22, 23]
2	Personal safety unawareness	[22, 32, 41, 43, 44, 57, 58]
3	Lack of experience	[32]
4	Personal competency	[41, 42, 44, 57]
5	Increased workload resulting from rework, fatigue, and overtime	[4, 22, 32]
6	Bad temper	[59, 22]
7	Lack of safety education and training of workers	[12, 27-32, 41-45, 58]
8	Workers' overconfidence and tendency to take shortcuts	[22]
9	Workers' insufficient safety knowledge	[4]
10	Failure to meet of workers every week	[22]
11	Inadequate certified skill labour	[22]
12	Nedovoljno tehničko vodstvo	[22]
13	Nerealno trajanje projekta i cijena naručitelja	[22]

management to prioritise the enhancement of job satisfaction among workers to improve safety at construction sites [53]. The pressure exerted by management on construction workers can also influence their safety behaviours [54]. Owing to hard work and poor working conditions, few young people want to do the job in China, and only older people do this job, leading to the frequent flow of workers in construction. As a result, experienced and skilled workers are insufficient. Therefore, before commencing work, it is imperative for the project manager to verify the safety knowledge and skill levels of construction workers to formulate corresponding safety training plans [55, 56], Table 6.

3.7. Formwork/crane collapse/scaffolding failure and overload factors

Several types of collapse accidents occur in the construction of high-rise buildings, including foundation pit, scaffolding, crane, and formwork collapses [23]. Luo [17] indicated that a defective scaffold design was the main reason for formwork collapse/scaffolding failure. During the design phase, there should be a special checking report on scaffold bearing capacity. Prior to utilisation, a construction unit is required to preload the scaffold to ensure safety. Xu [23] adopted the fault tree analysis (FTA) method and pointed out that the reasons for the collapse of the scaffolding/formwork also included overloading, incorrect installation, quality defects, and substandard materials. Regarding crane collapse, crane operators are responsible for effective crane control and compliance with safety guidelines. If crane maintenance specifications and operations are not properly followed, injuries and property damage can occur. Zaini et al. [61] stated that operational and technical issues are the main causes of crane accidents at construction sites in Malaysia, Table 7.

3.8. Safety management factors

Safety management factors consist of safety production responsibility systems, safety inspections, safety education and training, accident prevention and treatment, subcontractor control, budget allocation for safety management, and suitable supervision. Xu et al. [23] indicated that the safety production responsibility system is the core of safety production rules and regulations. The safety production responsibility system is one in which leaders at all levels, functional departments, engineering and technical personnel, and job operators

Table 7. Formwork collapse/scaffolding failure and overload factors

Br.	Safety risk factors	References
1	Defective design of scaffold	[17, 23]
2	Failure to disclose and inspect as required	[4, 23]
3	Poor material quality of scaffolding used	[22]
4	Scaffolds are inadequately fastened or tightened	[22]
5	Unskilled and negligent workmanship in erection of scaffolds/formwork	[22]
6	Crane collapse	[22]
7	Formwork collapse	[17, 23]
8	Incorrect loading or improper placement of equipment/supplies	[22, 17, 23]
9	Unskilled crane operator	[22, 17, 23]
10	Operating equipment without proper authorisation	[22, 17, 23]
11	Incorrect use of equipment	[22, 17, 23]

Table 8. Safety management factors

Br.	Safety risk factors	References
1	No safety production liability system	[6]
2	Lack of special construction plans for dangerous sub-projects	[6]
3	Control of subcontractor	[6, 25, 27, 37]
4	Lack of budget allocation on safety management	[12, 28, 29, 32]
5	No suitable supervision	[41, 43, 44, 57, 58]
6	No emergency response plan	[6, 37, 60]
7	No special guide for the installation and disassembly operations	[4, 17, 23]

are responsible for safe production at all levels during the labour production process. Even if the construction unit has established a safety production responsibility system and safety management system, some enterprise leaders place too much emphasis on the management of economic benefits, neglecting the importance of safety management work, resulting in the ineffective implementation of relevant laws, rules, regulations, norms, and plans. The requirements for regulations and plans cannot be implemented effectively [62]. Moreover, high-rise construction workers in China lack sufficient expertise and awareness of safety standards and practices; therefore, safety education and training are particularly important, Table 8.

4. Assessment methods for the safety risk level

In Section 3, the safety risk factors identified by the author are summarised into eight main factors, which is the first step in addressing safety issues.

Effective risk prioritisation not only helps managers take action to reduce or eliminate urgent risk factors through safety measures but also allows for better allocation of limited budgets, reducing costs, and freeing up resources to further mitigate risks in projects. Therefore, this section proposes effective methods for assessing the 60 safety risks identified in Section 3.

Construction processes and procedures comprise numerous tasks, processes, and requirements, involving numerous factors and considerations in decision-making. Construction safety in high-rise building projects can be enhanced by utilising safety evaluations through a decision analysis approach. Therefore, multicriteria decision-making (MCDM) methods have been applied to assess safety risks when decision makers need to select the best option from among many alternatives [63]. MCDM includes the analytic hierarchical process (AHP), technique for order performance by similarity to ideal solution (TOPSIS), VIKOR, best–worst method (BWM), decision-making trial and evaluation laboratory (DEMATEL), and unascertained measure theory (UMT). Recognising various MCDM techniques and outlining their respective advantages and disadvantages is crucial for establishing a robust research framework [64]. Decision makers can select the most suitable and effective method among MCDM to assess various types of risk in high-rise building construction. MCDM includes several steps: substitutions, criterion creation, evaluation options, criterion weighting determination, and the ranking method [65].

To rank alternative tower crane layout plans in high-rise modular integrated construction (MiC), a new decision-making framework that integrates MCDM techniques, specifically fuzzy-AHP and TOPSIS, was proposed by Zhang et al. [89] to evaluate and rank alternative crane layout plans. TOPSIS is a technique based on the concept that the best alternative to an MCDM problem is the one closest to its ideal solution. A knowledge-based decision support system (KDSS) was exploited by Rahman et al. [68] to aid in the selection of roofing materials, where the TOPSIS method was applied during the multi-criteria analysis process and functioned as a component of the inference engine within this technology. Based on the TOPSIS method, Li et al. [69] developed a fire risk assessment system for coal mines.

To enhance project safety, it is essential to select contractors based on various criteria during the bidding phase. A method is required to generate a compromise ranking for a set of alternatives based on their proximity to the ideal solution. Therefore, Liu and Yan [70] utilised a combined AHP–VIKOR model to deal with the bidding procedure for construction projects. The authors evaluated a group of four candidates based on five performance criteria: quotation, construction design, firm competence, quality, and time schedule. Furthermore, both methods were used to calculate the priority eigenvector and determine the final ranking of the alternatives [63].

Subcontractor selection is crucial for a project's success. Contractors must consider many aspects of the subcontractor; therefore, DEMATEL, developed in the 1970s, was specifically designed to analyse and map the causal relationships between factors in a complex system. This helps identify which factors are influential and how they affect one another. DEMATEL is a robust method for collecting collective insights to create a structural model. It effectively maps causal interactions among complex factors using a cause–effect diagram and dependency matrix, as highlighted by Tzeng and Huang in 2011 [71]. Bavafa et al. [85] employed DEMATEL to develop a network structure for the interdependent safety program factors. His findings aligned with those of Hallowell and Gambatese [72], who identified subcontractor selection, employee involvement, and job hazard analyses as key elements of effective safety programs.

To determine the most significant safety risks in high-rise buildings, the AHP was first used in construction applications by Skibniewski et al. [66], who elaborated on the advantages of this technique for technical and economic evaluations. A case study demonstrating the selection process for a tower crane was presented to illustrate the applicability of this method. The AHP system was employed by Shapira et al. [67] to develop an equipment selection model for construction projects. The model hierarchy was organised by dividing the problem into four main criteria and eighteen sub-criteria, which were analysed from three perspectives: cost evaluation, benefit evaluation, and overall assessment. Comprising both quantitative and qualitative criteria, the primary issue with the AHP method is the inconsistency in the paired comparison matrix, which can result in ambiguous outcomes. Moreover, as the number of criteria increases, the requirement for paired comparisons also increases, which poses an additional challenge. To address the challenge of inconsistency in the paired comparison matrix in the AHP, Rezaei et al. [73] suggested the BWM technique for reducing the quantity of paired comparisons needed through structured paired comparisons, which assists decision-makers in making well-reasoned and logical decisions to address pertinent factors and criteria in decision-making processes through effective weighting. In contrast to Rezaei [73], Nawaz et al. [74] applied the BWM to rank cloud services directly, in which a scale of 1 to 9 was utilised to capture expert preferences for determining the weights of the criteria. He also utilised the best–worst method (BWM) to assess a delivered product and evaluate the provider's performance.

In the construction industry, fire accidents in high-rise buildings are often fatal, both during construction and in completed structures. To assess the magnitude of fire risk, Li et al. [84] established a fire risk assessment index system suitable for high-rise buildings under construction, in which the unascertained measure theory was utilised to develop a fire risk assessment model for high-rise buildings under construction. They conducted a case study in Xi'an, China, and verified the rationality and feasibility of the fire risk assessment system and assessment model. The unascertained measure theory was first proposed by Wang et al. [75]. Unlike random, gray, and fuzzy information, unascertained information denotes a situation in which individuals lack a complete understanding of the precise quantitative relationships or states under consideration, which leads to subjective and cognitive uncertainty in the minds of decision makers and evaluators. Liu et al. [76] developed an unascertained mathematical theory and introduced an assessment model based on the unascertained measure theory. This model utilises real numbers within the range [0, 1] to effectively characterise uncertain states or ambiguous natures. Therefore, the unascertained measure theory has been widely used in many fields such as chemical safety assessment [77], ecological risk evaluation [78], pipeline risk assessment [75], geotechnical risk assessment [79, 80], mining risk evaluation [81], geological risk assessment [82], and social evaluation [83]. The unascertained measure theory provides an effective and quantitative approach for analysing diverse uncertain factors. Moreover, it mitigates the inadequacies of risk assessment indices resulting from uncertainties in influencing factors and alleviates subjectivity issues in risk assessment outcomes stemming from expert scoring. However, this method cannot provide a dynamic assessment index system.

To determine the critical safety factors, the RII was employed to measure the relative significance of different safety factors in the construction context. This helps quantify the importance of each factor according to the respondents' feedback. Confirmatory factor analysis (CFA) is used to test whether a set of observed variables represents the number of latent (unobserved) factors that a researcher expects based on a pre-existing theory.

Table 9. Assessment methods for safety risks

Assessment methods	Definition	Advantages	Disadvantages	References
Unascertained measure theory; entropy weight method	Develop a fire risk assessment model	It can effectively and quantitatively analyse various uncertain factors, mitigate the incompleteness of risk assessment indices due to the uncertainty of influencing factors, and address the subjectivity in risk assessment results caused by expert scoring.	No dynamic assessment index system	[84]
Decision-making trial and evaluation laboratory (DEMATEL)	Establish a network structure of interdependent safety program factors. The causal interactions among these factors were illustrated using a cause-and-effect diagram and dependency matrix.	Facilitates the efficient identification of all cause-and-effect relationships and key factors, even within highly complex systems.	Cannot determine the weight of individual criteria, subjective judgments, misinterpretation of results.	[85]
Relative importance index (RII)	Ranking of critical safety factors according to the respondents' feedback by using the RII value.	It is accurate, as a quantitative analysis using a clear numerical ranking of the factors.	RII assumes that all factors are equally important, which may not always reflect reality.	[86]
The best–worst method (BWM)	Addresses the influential factors and criteria in decision-making for weighing to identify the most significant safety risks in high-rise buildings.	It addresses the issue of inconsistency in the paired comparison matrix, which is a major challenge in the AHP method, and reduces the number of paired comparisons through structured pairwise comparisons.	Sample dependency	[87]
Fuzzy multi-criteria optimisation and compromise solution (FUZZY VIKOR)	Weighting and prioritising influential factors in safety risks in high-rise construction buildings	A robust method for addressing multi-criteria decision-making problems with conflicting criteria, used to prioritise the most significant safety risks.	Complexity; the interpretation of fuzzy VIKOR results can be challenging	[87, 88]
Fuzzy-AHP and TOPSIS	Evaluate and rank tower crane layout plans in high-rise modular integrated construction (MiC). TOPSIS is employed to assess and rank alternative tower crane layout plans.	Fuzzy-AHP converts experts' subjective perceptions into precise numerical values, while TOPSIS provides a straightforward computational process and yields more practical results.	Construction planners often face challenges in simultaneously generating alternative layout plans and conducting performance evaluations.	[89, 90, 91, 92]
Confirmatory factor analysis (CFA)	To test whether the survey data fit a hypothesised measurement model.	Verify whether proposed theoretical models fit well with actual data, thereby validating the effectiveness and reliability of the theory.	CFA requires a relatively large sample size to ensure accurate estimation of model parameters and reliable inference	[93]
FEAHP–PRAT Method	Combine the fuzzy extended analytical hierarchy process (FEAHP) and the proportional risk assessment technique (PRAT).	The synergy between PRAT and MCDM empowers decision-makers to identify effective actions for addressing safety issues. It assists in prioritising protection measures and allocating resources efficiently to maximise accident prevention.	It needs sensitivity analysis to the weights imposed to the A and R factors while computing the CFP.	[92]
Risk network for housing construction accidents (RNHCA).	A quantitative assessment model that identifies key risk factors and high-risk chains within the evolving risk network.	It can identify high-risk chains, assess the status of the risk system, and dynamically simulate the evolution of the risk factor network.	A good deal of accident investigation reports must be collected, classified, and analysed to understand the patterns and evolution of risk networks.	[94]

The budget for safety in construction projects is usually tight. To achieve maximum health and safety protection with the minimum cost, Koulinas et al. [92] proposed a safety risk assessment procedure employing the fuzzy extended analytic hierarchy process (FEAHP) to prioritise risks at construction sites. They further combined the FEAHP with the proportional risk assessment technique (PRAT) to identify effective actions for addressing safety issues. The AHP reflects the decision maker's experience and values, whereas the PRAT utilises historical accident data. This combined process aids decision makers in prioritising protection measures and optimising resource allocation for maximum accident prevention.

To identify the critical risk factors and high-risk chains in the development of the risk network. The RNHCA is specifically designed to analyse and manage the risks associated with accidents in housing construction projects. Unlike traditional risk assessment methods that may treat risks in isolation, RNHCA focuses on the interrelationships between risks by defining a risk threshold for each factor and assigning a risk value based on the correlation between the risk factors. Furthermore, it dynamically simulates the evolution of a risk-factor network.

To more directly understand the applicability and practicality of each evaluation method, this section conducts an in-depth analysis of each of the advantages and disadvantages of the approaches in Table 9, which will help decision-makers choose the most appropriate method to evaluate construction safety risks.

5. Mitigation techniques for safety risks

The objective of this study is to reduce safety risks to an acceptable level, not the lowest level, by taking the most economic measures. Therefore, this section further explores mitigation solutions and establishes a framework that presents strategies to mitigate the main safety risk factors identified in Section 3.

In Section 4, we found that the most critical safety risk is falling from a height (FFH) during high-rise building construction, according to prior literature. As one of the main safety risk factors, FFH is regarded as the most hazardous because of its frequent and fatal consequences [95-97], it poses a huge threat to the lives of construction workers, making it crucial to implement best practices during the design phase of construction. To address this issue, Zhang et al. [98] developed a BIM-based 3D simulation model to identify and prevent fall hazards during the construction planning phase, which was successfully implemented in two case studies. A personal fall arrest system (PFAS) serves as a crucial safety measure for workers at risk of falling during their tasks. It acts as the ultimate safeguard, halting persons' falls as they become endangered while working at heights. A PFAS consists of a suitable body-holding device, such as a harness, a fall energy-absorbing element, an anchor line, an anchor point, connecting equipment, snap hooks, grab wires, and self-retracting lanyards [99]. It provides a vital layer of protection for workers at height, thus reducing the risk of injury or fatality in the event of a fall. However, a drawback is that the initial investment in PFAS can be enormous.

The safety of construction workers in high-rise building projects is ensured by the use of PPE. However, a significant issue arises from workers' negligence in wearing PPE properly while on the job. To address this concern, an innovative cyber-physical system (CPS) was introduced to monitor how workers wear PPE at construction sites in real time. Furthermore, Gómez-de-Gabriel et al. [100] proposed a sensor system based on Bluetooth low energy (BLE) beacons, and the wearables + BLE beacons technique involves integrating inertial sensors into the harness, which can detect the absence of movement when the worker is no longer wearing the harness. Fortunately, the cost of the solution is not very high. However, its disadvantage is that it must be integrated with other computer techniques that require professional training.

For safety management factors, the most effective safety measures must be taken to reasonably control construction safety risks. Therefore, it is necessary to select the most effective and economical measures for specific risks. As an MCDM, TOPSIS was used to rank safety measures based on their risk-mitigation effects. INamely, to identify the most effective measures [101], SPA was employed to assess the pre-mitigation and post-mitigation risk levels based on the uncertainty theory. In order to assist decision-makers in formulating cost-effective risk-control strategies [102], set pair analysis (SPA) is combined with TOPSIS to control the construction risks to an acceptable level instead of excessively to the minimum level, i.e., among the safety-measure combinations that can reduce the risks to an acceptable level, the alternatives that require the fewest safety measures are considered the optimal solutions. However, it does not account for risk-related losses; instead, it considers only the number of safety measures as a proxy for risk-mitigation costs. In addition, a BIM-based safety management approach that digitally designs and visualises onsite conditions was introduced by [110], which can assist safety managers in developing more effective plans with the assistance of a BIM-based three-step automated safety-risk recognition process.

Crane accidents not only pose a threat to construction workers but also cause damage to nearby facilities, endangering pedestrians. Consequently, cranes are regarded as the backbone of the construction of high-rise buildings. To minimise the safety risks of cranes and to qualitatively develop a generic model for tower crane safety, which thoroughly outlines the system levels and causal pathways of contributing factors, Zhou et al. [104] developed a generic AcciMap model, which not only aids in comprehending the tower crane safety system but also offers a structured framework for preventing and analysing tower crane accidents. Identifying the crucial factors and key dimensions within the tower crane safety system can facilitate the establishment of an evaluation and control system, thereby enhancing the overall tower crane safety management. The

Table 10. Summary of safety risk mitigation techniques

Mitigation techniques	Applications	Advantages	Disadvantages	References
Personal fall arrest system (PFAS)	A device designed to interrupt a falling worker's fall, serving as the last line of defence for individuals in positions where they are at risk of falling.	Provides a vital layer of protection for workers at height, reducing the risk of injury or fatality in the event of a fall.	The initial investment in PFAS can be significant; its use requires proper training, which can be time-consuming and challenging.	[99]
TOPSIS–SPA-based method	Defining the set pair, establishing the connection degrees, and assessing the risk level. The ideal solution of risk index i is set as the risk score after mitigation, whereas the anti-ideal solution of risk index j is set as the original risk score without mitigation.	This method accounts for the many-to-many relationships between safety measures and risk factors, helping decision-makers identify the most effective combinations of safety measures.	It does not account for risk-related losses; instead, the method uses the number of safety measures as a proxy for risk-mitigation costs.	[102]
The AcciMap technique	For tower crane safety in construction sites	Provides an overview of the contributing factors and causal flows within the system, enabling the development of a proactive risk management process to systematically formulate safety risk prevention and mitigation strategies.	Requires a large amount of data support and requires high professional competence from personnel	[104]
BIM, GPS, GIS, RFID, AR VR, laser scanning, and quick response (QR) coding	Generate a wide range of comprehensive data and information about a project, with a particular focus on enhancing construction site safety.	Computer-vision methods have the potential to address specific issues during construction, including progress monitoring, efficiency enhancement and analysis, as well as health and safety monitoring.	Steep costs, limited proficiency in BIM, insufficient training opportunities, governmental regulations, security issues, deficient industry norms.	[109]
BLE system (Bluetooth low energy)	Preventing individuals from falling from height by monitoring the proper use of harness.	It enables easy relocation of beacons and operates without requiring calibration, communication infrastructure, external processing support, or frequent configuration updates.	Lack of real-time feedback to workers due to remote monitoring. Workers are able to cheat the system by removing the harness while keeping it attached to the lifeline.	[111, 112]
BIM-based design for safety planning, management, and rule-based safety checking	A BIM-based safety planning approach—by digitally designing and visualising onsite conditions—can assist safety managers in developing more effective plans. This includes a BIM-based three-step automated safety-risk recognition process.	Safety-planning platform that integrates an automated safety-checking approach using BIM. These technologies enhance workers' capacity to recognise hazards and plan and manage safety effectively.	These technologies have not yet been adequately tested, validated, or proven for industrial application.	[110]
BIM Integration with cloud, sensors, real-time tracking technologies	Cloud technology, radio-frequency identification (RFID), and wireless sensor networks integrated effectively with BIM, potentially offering significant benefits for construction safety.	BIM provides a novel communication method that facilitates the flow of information both forward and backwards.	One drawback of BIM is the frequent need for software updates and upgrades every three years, increasing the overall cost of implementing the technology initially.	[36, 110]
BIM process flow	Offering a near-realistic environment for safety training of construction workers and job hazard identification (JHI).	Support construction workers' safety training and JHI during the pre-construction stage.	Changing from the conventional method of construction safety and JHI to an advanced one may require significant capital investment.	[99, 114]

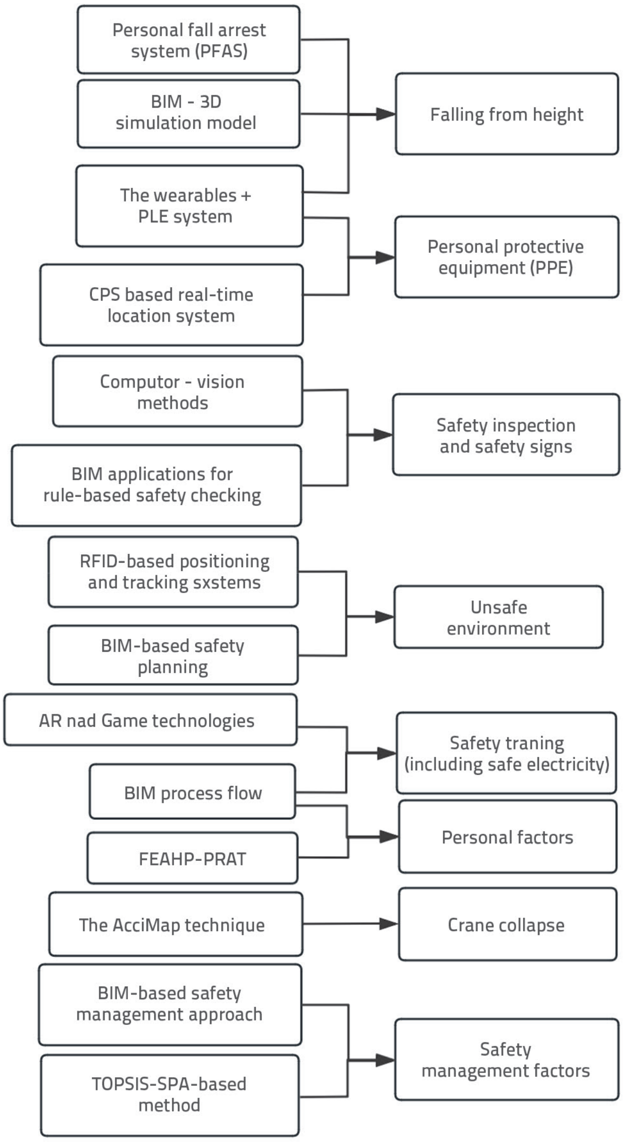
drawback of the AcciMap technique is that it requires a large amount of data support and highly professional competence from personnel. Similarly, construction on deep foundations is a risky process; however, with code compliance, construction supervisors can assess safety risks before proceeding. In BIM models, the safety of deep-foundation construction can be effectively monitored using BIM-based code compliance.

Temporary work is a leading cause of accidents in high-rise building projects, often resulting in fatalities and injuries [114]. To create a safe working environment, Azhar et al. [103] developed five safety plans, simulations, and videos based on BIM: 4D excavation simulations, fall protection plans, electricity safety plans, crane management plans, and emergency response plans. The results validated that BIM-based safety planning is moderately to highly effective and accurate for identifying hazards and communicating safety plans to workers. Radiofrequency identification (RFID) technology has gained popularity in various fields. Its greatest advantage is high speed [116]. Cai et al. [105] proposed a combined RFID and GPS system tailored for construction sites, emphasising the importance of accurate indicators for assessing the reliability of RFID-based positioning and tracking systems in the construction context. Abd Razak et al. [116] introduced the design for manufacturing and assembly (DfMA) method to reduce onsite temporary work and the dependence on foreign unskilled labour, thus creating a safer workplace.

Safety inspections are essential and must be properly implemented to minimise accidental accidents and fatality rates. However,safety inspections at construction sites are often ineffective and merely formal. As a result, researchers are attempting to utilise computer-vision methods to investigate special issues during construction, such as progress monitoring [106], efficiency enhancement and analysis [107], and health and safety monitoring [108], which allows the collection and analysis of digital images and the extraction of high-dimensional data from the real world to generate knowledge, thus enhancing management decision-making. Manzoor et al. [109] integrated BIM with emerging digital technologies such as GPS, GIS, RFID, AR, VR, laser scanning, and quick response (QR) coding for monitoring and inspection purposes. The authors also developed a research framework that integrated BIM with emerging digital technologies to mitigate construction accidents, thereby extending the role of BIM with emerging digital technologies in construction safety management. Furthermore, [110] integrated BIM with rule-based safety checking and proposed an automated safety-checking method utilising BIM, which improved workers' ability to identify hazards and effectively plan and manage safety.

For workers with low knowledge levels and a lack of experience, safety meetings and well-organised safety training are essential. [117] demonstrated that construction labour productivity is affected by factors such as site safety, clarity of instructions, and exchange of information at the job site. It is crucial to inform workers of potential safety hazards during the preconstruction stage. [110] revealed that emerging digital technologies, such as BIM, VR, AR, GIS, and gaming technologies, allow safety managers to visualise and analyse construction sites virtually to devise effective safety training and proactive safety measures.

Figure 2 shows the mitigation strategies for the eight main safety risk factors identified in Section 3.



Figurw 2. Research framework for the mitigation strategies of the eight main safety risks identified in Section 3

The combination of FEAHP and PRAT (as mentioned in Section 4) enables decision makers to pinpoint effective strategies for improving workers' safety awareness. This aids in prioritising protective measures and efficiently allocating resources to enhance accident prevention efforts. Furthermore, [113] conducted a BIM process flow to support a nearly realistic environment for safety training and job hazard identification for construction workers. This introduced an innovative communication method that enhanced the flow of information in both directions.

However, the drawbacks include steep costs, limited proficiency in BIM, insufficient training, deficient industry norms, and an absence of incentives for BIM integration in construction endeavours. Regarding the cost of safety measures, medium and small companies may consider the most critical safety risks and choose the most economical and necessary techniques, such as the BLE system and PFAS. For large construction companies and those with higher safety requirements, BIM, clouds, sensors, real-time tracking technologies, BIM process flow, and job hazard identification (JHI) are required to make construction safer.

Table 10 provides a detailed overview of safety risk mitigation techniques aimed at minimising accidents in high-rise building projects.

6. Discussions

The ultimate goal of this study is to provide feasible measures to mitigate safety risks based on identification. This in-depth review evaluated 84 research papers, of which 78 were journal papers, and the rest were conference papers. The result shows that 8 main safety factors and 60 sub-factors were identified, and nine assessment methods were developed to evaluate the impact of these safety factors on construction sites. Finally, the mitigation techniques tailored to the identified eight main safety risks were obtained using the framework shown in Fig. 2.

The assessment methods for safety risks include MCDM and non-MCDM methods. AHP, TOPSIS, VIKOR, BWM, DEMATEL, unascertained measure theory (UMT), and FEAHP–PRAT are among MCDM. Non-MCDM involves RII, CFA, and risk networks for housing construction accidents (RNHCA) methods. The criteria for selecting these methods are listed in Table 9.

The mitigation techniques involve the AcciMap technique, BIM-based fall hazard identification approach, BIM-based safety management approach, personal fall arrest system, BLE system, video camera technique, BIM-based 4D integrated technique, cyber-physical system (CPS), RFID-based real-time locating system, and multicriteria decision making (MCDM) technique. FEAHP–PRAT and TOPSIS–SPA are MCDM techniques used for risk assessment and the selection of suitable strategies for safety risks. The selection criteria for the AcciMap technique are based on its ability to illustrate how the conditions, decisions, and actions of various actors interact to produce the incident under analysis. The selection criteria for the BIM-based fall hazard identification approach rely on an automated rule-checking framework to identify and mitigate fall-related hazards. The selection criterion for the BIM-based safety management approach is whether it can monitor and display workers' positions in real time and issue timely alerts to at-risk workers.

Today, the construction industry provides the essential infrastructure and services necessary for the development of civilisation, on which people depend for living and working [118]. Therefore, it is important to reduce safety risks and promote project success. This study provides valuable guidance for construction project managers, engineers, safety officers, and stakeholders involved in construction projects, particularly high-rise buildings. This framework offers a practical way to mitigate the safety risks that contribute to accidents in high-rise building projects, ultimately enhancing the safety of construction projects.

7. Conclusion

This research aims to identify and assess safety risks as well as to seek out mitigation techniques for high-rise building construction. This review discusses the research conducted between 2004 and 2024, as this timeframe corresponds to a period marked by significant technological interventions in traditional construction practices. This comprehensive review of safety risks in high-rise building construction discusses the current challenges in the adoption of technology for improving construction safety scenarios for future research. The results show that various emerging digital techniques have been employed to substantially improve construction safety. However, the effectiveness and reliability of these digital technologies remain largely theoretical and await practical validation in future research endeavours. The findings of this study will help further investigate safety risks in high-rise building construction.

This study is distinctive in that a) it conducted a systematic review of the latest advancements in accidental safety risks and current challenges in the adoption of mitigation technologies, and b) it provides suggestions and future orientations that offer guidelines on how to address the drawbacks of the current prevention measures to improve building construction safety. From a practical perspective, the findings of this study will provide governments, construction companies, engineers, and researchers with an intelligible framework to assist them in grasping cutting-edge techniques and choosing suitable techniques for themselves. In summary, this study achieves the goal of making high-rise construction sites safer and more cost-effective.

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