



A bibliometric study on technology usage for occupational safety and health risk assessment in construction industry

Xiaosheng Su, Ka Yin Chau, GTS Ho, Ho Tung Yip & Yuk Ming Tang

To cite this article: Xiaosheng Su, Ka Yin Chau, GTS Ho, Ho Tung Yip & Yuk Ming Tang (13 May 2025): A bibliometric study on technology usage for occupational safety and health risk assessment in construction industry, Journal of Asian Architecture and Building Engineering, DOI: [10.1080/13467581.2025.2499727](https://doi.org/10.1080/13467581.2025.2499727)

To link to this article: <https://doi.org/10.1080/13467581.2025.2499727>



© 2025 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group on behalf of the Architectural Institute of Japan, Architectural Institute of Korea and Architectural Society of China.



Published online: 13 May 2025.



Submit your article to this journal [↗](#)



Article views: 673



View related articles [↗](#)



View Crossmark data [↗](#)



Citing articles: 1 View citing articles [↗](#)

A bibliometric study on technology usage for occupational safety and health risk assessment in construction industry

Xiaosheng Su^a, Ka Yin Chau^{a,b}, GTS Ho^c, Ho Tung Yip^d and Yuk Ming Tang^{e,f}

^aDepartment of Human Resources, Chongqing Industry Polytechnic College, Chongqing, China; ^bCentre for Quality Standard & Management, The Hang Seng University of Hong Kong, Hong Kong, China; ^cDepartment of Supply Chain and Information Management, The Hang Seng University of Hong Kong, Shatin, Hong Kong, China; ^dThe Jockey Club School of Public Health and Primary Care, The Chinese University of Hong Kong, Hong Kong, China; ^eDepartment of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong, China; ^fFaculty of Business, City University of Macau, Macau, China

ABSTRACT

The recent research efforts in the use of visual imaging techniques such as artificial intelligence (AI), virtual reality (VR), and the Internet of Things (IoT) provide the opportunity to enhance risk assessment methods. However, our understanding of enabling technologies to enhance construction occupational safety and health is still insufficient. This paper uses bibliometric approaches to comprehensively review construction occupational safety and health hazards. The bibliometric data of the publication titles, abstracts, keywords, citation counts, and impact factors were thoroughly examined to understand the literature landscape and identify the predominant research themes for possible future research trends in construction risk assessment. Different risk analysis and assessment (RAA) models adopt different approaches tailored to identify and evaluate risk exposures, including the Analytic Hierarchy Process (AHP) model and the Building Information Management (BIM) system. The adoption of technologies in construction safety and health risk assessment has significantly increased over the past decade, particularly between 2020 and February 2025, highlighting its interdisciplinary applications and focus on safety training methods. Future research should focus on enhancing safety management by integrating VR and wearable sensors, while expanding data sources and interdisciplinary approaches, especially in response to COVID-19 challenges.

ARTICLE HISTORY

Received 27 December 2024
Accepted 24 April 2025

KEYWORDS

Bibliometric analysis; construction; occupational safety and health; risk management; analytic hierarchy process

1. Introduction

Risk management has emerged as a crucial aspect of overall sustainability management and social responsibility (Chellappa et al. 2021). Corporations face various risks, broadly categorized into business, non-business, and financial risks. Among these, operational risk, a subset of business risks, is often regarded as more frequent and serious. This is particularly true in high-risk industries such as oil and refinery plants, chemical manufacturing, and construction. In these sectors, there is a heightened concern regarding exposure to the operational environment, including potential damage to equipment and the risk of human injury (Goerlandt and Li 2022). Shafique and Rafiq (Shafique and Rafiq 2019) have highlighted that the construction industry is inherently hazardous. Both non-fatal and fatal occupational injuries are prevalent due to their specific nature. The industry is characterized by hazards, complications, and unpredictable work activities. Unlike industrial settings that often follow a matrix-based manpower deployment, construction sites are dynamic as working conditions change daily. Furthermore, uncontrollable environmental factors,

such as adverse weather on windy or rainy days, add to the risks. The industry faces potential dangers from ongoing changes, diverse resource usage, and challenging working environments, including exposure to vibration, noise, and weather fluctuations. Additionally, Suárez Sánchez et al. (2017) have emphasized that site conditions, construction materials, dimensions, and building designs vary significantly, necessitating a learning curve and adaptation for workers transitioning from one site to another.

Despite efforts by industrial practitioners and academic researchers to reduce the number of construction accidents, the construction industry remains one of the most dangerous industries globally (Suárez Sánchez et al. 2017). According to the International Labour Organization (ILO), the construction industry accounts for 35% of all workplace fatalities, with approximately 60,000 fatal accidents occurring annually at construction sites worldwide (Chetty et al. 2024). Additionally, 30% of construction workers suffer from musculoskeletal diseases or back pain (Zhang et al. 2020). Achieving the goal of “zero injuries or

CONTACT Yuk Ming Tang  mfymtang@polyu.edu.hk  Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong, China

© 2025 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group on behalf of the Architectural Institute of Japan, Architectural Institute of Korea and Architectural Society of China.

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

accidents" in the construction industry is a significant challenge (Chellappa et al. 2021; Zhou et al. 2015). There is an urgent need for research on construction occupational safety and health risk assessment by the research community and industrial practitioners.

Operational risk management is a framework for identifying, evaluating, and prioritizing risks, followed by a risk control process to reduce and manage unforeseeable damages (Saisandhiya 2020). To quantify risk levels, there are three major types of Risk Analysis and Assessment (RAA) models: hybrid, qualitative, and quantitative approaches. Qualitative approaches rely on the personal judgment of engineers or safety managers, while quantitative techniques use actual accident data for mathematical model calculations. Hybrid methods combine elements of the dynamic environment and complex scenarios present in the construction industry (Hill et al. (2019)). Recently, key objectives in construction risk assessment have focused on enhancing project safety management practices (Sanni-Anibire et al. 2020). Typically, construction management relies on the professional judgment of project teams to evaluate the expected level of work hazards (Muñoz-La Rivera et al. 2021). To estimate risk levels, qualitative and quantity risk analysis methodologies such as Checklists, HAZOP, What-if Analysis, and Fault Tree Analysis (FTA) diagrams can be employed. In contrast, mixed approaches may include techniques like Fuzzy ABC classification (Yung et al. 2021) and Analytic Hierarchy Process (AHP).

In addition to knowledge-based risk assessment studies, visualizing construction site activities is also important. Two-dimensional (2D) drawings provide limited information for risk identification due to their static visual information at one specific phase of the project life span (Zou et al. 2019). Building information modelling (BIM) has been shown to significantly enhance construction risk recognition and minimization (Fagnoli and Lombardi 2020; Karaz et al. 2020). BIM enables more proactive and effective construction safety and risk management (Sami Ur Rehman et al. 2022), offering a dynamic graphical representation of the construction site that efficiently incorporates occupational safety and health data. The semantic retrieval feature reflects the continual change of related safety data of a specific object at each stage of a project (Du et al. 2018).

Many research efforts have applied sensing technologies such as AI and IoT for innovative product design to decrease the workforce relevant to construction safety supervision (Tang et al. 2023; Yung et al. 2021). However, numerous barriers exist in using such technologies in on-site safety supervision, including identification and registration of possible hazards, simultaneous identification of unsafe events, and tracking and reporting sensors. BIM technology could address these challenges by recognizing risk factors or

hazards at the design stage, visualizing them as the project progresses, and adding wearables or sensors for real-time detection of risk status when an accident happens (Toh et al. 2023). Combining wearable and mobile devices with BIM may foster the acceptance of VR systems and immersive technology for risk assessment and training (Leong et al. 2022; Tang et al. 2023). Piroozfar et al. (Piroozfar et al. 2019) highlighted that the use of VR or augmented reality (AR) on risk assessment and risk bi-directional communication could help front-line staff "see" or "visualize" risks or hazards in a dynamic construction site at different project stages.

The past review studies in the construction industry focus on research including particulate matter pollution (Cheriyana and Choi 2020), traditional and fuzzy occupational risk assessment approach (Gul et al. 2021), supply chain management (Wu et al. 2019), the effect of construction safety on organizational or group features (Suárez Sánchez et al. 2017), and deep learning application (Akinosho et al. 2020). Despite the adoption of various technologies and the application of different health risk assessment methodologies for occupational safety in the construction industry, there are still few reviews that systematically investigate the technologies and methods used for occupational and health risk assessment. Akinlolu et al. (Akinosho et al. 2020) also indicated that many past studies on the construction industry concentrated on specific digital technologies, such as real-time and sensor-based technologies and BIM for construction safety and health management. Zhou et al. (Zhou et al. 2015) and Sanchez et al. (Suárez Sánchez et al. 2017) criticized that various past research papers only provided the groundwork for the construction safety management process and incident/accident data rather than a systematic and comprehensive approach for understanding the technology used and assessment methods. Thus, this highlights a significant research gap in this field. A systematic analysis is essential for key stakeholders to understand future technology trends (Tang et al. 2024) and research directions (Geda et al. 2024), particularly in construction occupation safety and health risk assessment. Such an analysis would help identify emerging trends and share cutting-edge, state-of-the-art findings that are likely to shape future efforts in occupational safety and health risk assessment.

Among various systematic review approaches, bibliometrics facilitates quantitative analysis of key findings related to the development and characteristics of a specific research area (Li et al. 2023). Generally, bibliometrics is a multidimensional research discipline encompassing various areas, including fundamental, predictive, adaptive, and analytical scientometrics. It also includes methods such as co-citation analysis, citation analysis, co-word analysis using keywords, and bibliographic

coupling based on citations (Li et al. 2023). Therefore, this study aims to conduct a systematic review of the existing literature to comprehensively examine the evolution of the subject. It employs an extensive bibliometric approach to investigate scholarly developments and emerging research trends, focusing on the application of state-of-the-art technological approaches for occupational safety and health risk assessment in the construction industry. In summary, this article addresses three key research questions through bibliometric analysis.

RQ1: What are the emerging research trends in subject areas and regions regarding the future application of technological risk assessment in construction?

RQ2: What are the performance and relationship among academia in the current construction occupational safety and health risk assessment research output?

RQ3: What are the key technologies and assessment models adopted for construction occupational safety and health risk assessment?

The research makes a significant contribution by applying bibliometric studies to the field of construction safety. Unlike earlier studies, which often focused on fragmented or narrow aspects of construction safety, this research offers a comprehensive and systematic bibliometric analysis. This approach enables a clearer understanding of current trends, influential works, and key technologies, as well as assessment models within the domain. Moreover, the study goes beyond traditional approaches by integrating advanced bibliometric tools and techniques to examine the interconnections between risk factors, assessment models, and safety interventions. These methodological advancements enhance the study's impact by providing a more robust framework for understanding and mitigating risks in construction projects. As a result, this research serves as a critical resource for researchers, policymakers, and practitioners striving to improve construction safety standards and practices.

This paper is divided into five main sections. In [Section 1](#), we provide the research background, settings, and objectives. [Section 2](#) discusses qualitative and quantitative risk assessment models in construction, BIM technology for risk assessment, and wearable devices. [Section 3](#) presents the data sources, search strategies, and data analysis. Based on the research methodology, key findings and results are provided in [Section 4](#). Finally, the concluding remarks are presented in [Section 5](#).

2. Literature review

2.1. Risk assessment models in construction

The analytic hierarchy process (AHP) has been widely utilized as a decision-making tool for construction risk assessment by prioritizing and evaluating risk factors. Kwok and Tang (Kwok and Tang 2023) used AHP to assess participant preferences, leveraging scores and weights to evaluate the rating and impact of risk items. However, AHP has been criticized for its simplicity in estimating impact and probability, as well as its reliance on subjective judgments. Limited academic efforts have been made to expand on the model's conceptualization of risk, probability, and impact. To address these limitations, researchers have extended AHP by integrating additional parameters relevant to construction, such as project cost, duration, quality, and claims. For instance, Dey et al. (1994) combined AHP with probability-impact (P-I) analysis to incorporate both objective and subjective risk assessments. Similarly, Riggs et al. (Riggs et al. 1994) used AHP to assign probabilities to decision trees, enabling the evaluation of cost, schedule, and technical risks through utility functions.

Several studies have explored the application of AHP beyond individual risk items to project-based risk exposures. Hamidah et al. (Hamidah et al. 2022) adopted AHP within a multi-criteria decision-making (MCDM) framework to estimate total project risk by aggregating threat scores based on the probability and impact of each risk. This approach allows for the comparison of relative risks among projects. Similarly, Shash et al. (Shash et al. 2021) integrated AHP with Utility Theory to develop a contingency model that recommends optimal cost contingency values for construction projects in Saudi Arabia.

In addition, fuzzy-based decision-making methods have been employed to enhance AHP's ability to address uncertainty and subjectivity in construction risks. For example, Abdelgawad and Fayek (Abdelgawad and Fayek 2010) highlighted the use of fuzzy AHP, Failure Mode and Effects Analysis (FMEA), and Fuzzy Inference Systems (FIS) for risk management in the construction industry. Khosravi et al. (Khosravi et al. 2020) combined AHP with fuzzy logic to prioritize risk elements and evaluate risks in complex construction projects. Other applications include using trapezoidal fuzzy numbers in AHP to address data inaccuracies in workplace safety assessments under wet and hot conditions (Zheng et al. 2012) and logarithmic fuzzy preference programming to examine risk elements in coal mine operations (Wang, Wang et al. 2016).

Despite its widespread application and extensions, AHP has received criticism for its data dependency and inability to reflect actual "risk costs." This limitation can hinder its practical utility in areas such as project

budgeting and progress monitoring. For instance, while AHP can help prioritize mitigation strategies for delays caused by adverse weather conditions (Hossen et al. 2015), its effectiveness diminishes when applied to cases with insufficient or non-representative data.

2.2. Risk assessment models with quantitative metrics

To overcome AHP's limitations, researchers have developed models that link risk assessment impacts to monetary values, providing more actionable insights for project stakeholders. For example, Kumar et al. (Kumar et al. 2021) proposed a Claim-Based Risk Assessment Model (C-RAM) to compute the cost implications of risks using project data. C-RAM evaluates risk incidents based on three criteria: the number of projects affected, the methods through which risks occur, and the claims resulting from those risks. This approach is useful in assessing financial risks, such as those arising from design flaws, by leveraging historical data to estimate the likelihood and financial impact of potential claims. By incorporating such models, project managers can allocate contingency funds more effectively.

However, the performance of these models can vary significantly across different project sizes. Large-scale projects, such as infrastructure or industrial developments (Korytářová and Hromádka 2021), often benefit from the detailed data inputs and computational resources required by models like C-RAM. These projects tend to have robust historical data and dedicated risk management teams, which enable the effective application of advanced quantitative metrics (Yazdi et al. 2024). In contrast, small-scale projects may struggle to implement these models due to limited budgets, reduced data availability, and a lack of specialized expertise. Simplified versions of C-RAM or AHP-based models may be more suitable for smaller projects, but this could lead to reduced accuracy and comprehensiveness in risk cost estimation. Small-scale projects often require adaptations or simplified frameworks to balance implementation costs with practical utility. The trade-offs between complexity, accuracy, and resource constraints suggest the need for further development of models that are scalable and adaptable to smaller projects (Aladayleh and Aladaileh 2024).

Furthermore, extensions of AHP have aimed to incorporate quantitative metrics to address real-world construction challenges across various project scales. For example, Ilbahar et al. (Ilbahar et al. 2018) adopted the AHP framework to identify performance indices for evaluating occupational health and safety systems.

Wang et al. (Wang et al. 2016) applied nonlinear vague AHP to examine managerial, environmental, and functional risks. While these enhancements attempt to bridge the gap between theoretical risk assessment methods and practical applications, the effectiveness of these models across different project sizes remains an important area for future research.

2.3. BIM technology for risk assessment

The increasing use of BIM technology as a visual tool for identifying risk exposures has shown significant potential in improving construction safety. Rodrigues (Analysis 2021) developed a 3D building model within the BIM environment, using the Revit application program, to mitigate occupational risks in construction. This plugin prototype integrates qualitative safety examination methods, including the adoption of safe objects, checklists, and job hazard analysis (JHA). These tools enable the identification of fall risks and facilitate the integration of correlated safety systems. However, the study lacks a critical analysis of potential challenges, such as BIM data compatibility issues and the scalability of the proposed plugin.

Similarly, Xu and Wang 2020 introduced a safety pre-warning instrument that combines a pre-warning safety system with a comprehensive risk assessment model. Their approach integrates AHP and expert knowledge with BIM safety simulations to extract safety information through computer perception. The system aims to dynamically analyze risks, provide actionable recommendations to risk owners, and classify risks into five levels (Analysis 2021). While this approach highlights the potential of BIM in proactive safety management, it does not address key technical limitations, such as data interoperability, the reliability of the classification process, or the practical challenges of implementing dynamic risk analysis in real-time construction environments.

2.4. Wearable devices

The use of wearables or sensors has increasingly gained attention for various purposes. The common purposes for wearables or sensors are to provide alerts or alarms to the workers at the site to avoid accidents and to identify the real-time location for inspections.

2.4.1. Real-time location monitoring

Kang et al. (Kang et al. 2021) developed a real-time monitoring system called "Monitoring for Noise, Vibration, and Dust (MONVID)" to calculate hazardous environmental emissions in real time. Gheisari et al. (Gheisari and Esmaeili 2019) explained how unmanned aerial systems (UAS) can be applied in various settings

to enhance safety performance. UAS can react more quickly than humans in remote, dangerous areas of job sites. Multiple sensors are used to support on-site safety control and transmit useful data to safety managers. The study indicated that using new technology such as UASs could generally improve safety performance. However, challenges such as adverse weather conditions, spatial limitations, and the need for advanced technical skills among operators can hinder the broader implementation of UAS technology in real-world construction settings (Albeaino and Gheisari 2021).

2.4.2. Alert and sensing

Panuwatwanich et al. (Panuwatwanich et al. 2020) examined how an uncomplicated ambient intelligence (Aml) system improved safety awareness among on-site construction workers to reduce fall accidents in high-rise buildings in Thailand. The design includes microwave sensors, an audio alarm, a light-emitting diode (LED), and a microcontroller. Despite its effectiveness, challenges such as workers' resistance to wearing the devices due to privacy concerns and hardware deployment difficulties have been noted (Bimpas et al. 2024).

Beyond occupational safety risks, Hashiguchi et al. (2020) concluded that biosensors could predict occupational health risk factors with an accuracy level of 89.2%. Akanmu (Akanmu 2020) highlighted that carpentry workers were highly at risk of musculoskeletal disorders. The risk exposures were evaluated employing the Postural Ergonomic Risk Assessment categorization, which is based on jobs including non-static postures and recurrent subtasks. A biosensor is mainly used in collecting construction workers' data to measure human stress factors as illustrated in (Jebelli et al. 2019) study. The construction industry is one of the most demanding sectors, and the authors proposed a theoretical framework for "non-invasive and non-subjective measurement" through wearable biosensors, allowing data collection without disrupting workers' tasks. However, challenges persist in integrating these technologies into everyday workflows.

2.4.3. Challenges in adoption

Despite the potential benefits, several major challenges hinder the widespread adoption of wearable technologies in construction. Initially, the substantial investment required for implementing these technologies and ongoing maintenance costs can create significant barriers for many construction firms (Ahn et al. 2019). Additionally, the expenses associated with technology, research, and development are often perceived as excessive, further discouraging investment. Moreover, the practicality of these technologies in real-world settings is often questioned. Workers may find devices cumbersome or intrusive, leading to resistance

to wearing them. Privacy concerns and the perceived usefulness of the technologies play crucial roles in influencing worker acceptance (Jebelli et al. 2019). Effective communication and education about the benefits of wearables are essential to overcoming this resistance, but they require time and resources that many firms may not have.

Additionally, integrating wearables into existing safety protocols is complex. Compatibility with current systems and the need for adequate training to ensure workers use these devices effectively pose additional challenges (Patel et al. 2022). The transition from pilot studies to real-time project implementation often reveals usability gaps, as devices may not perform as expected in dynamic construction environments. To differentiate from the existing body of knowledge, future research could explore strategies for addressing these barriers, such as developing cost-effective solutions, enhancing the user-centered design of wearables, and fostering a culture of safety that encourages adoption. By addressing these practical challenges, the construction industry can better leverage wearable technologies to enhance safety and health outcomes.

3. Research methodology

3.1. Data sources and search strategies

The Web of Science (WOS) is a comprehensive scientific search tool in this study. We acknowledge the existence of other databases, such as IEEE Xplore, SCOPUS, and ScienceDirect, and it is noted that most publications from these sources are included in WOS. This search strategy is also commonly employed in technology-related systematic reviews (Radianti et al. 2020; Tang 2022, 2025) and can be considered reliable. The inclusion criteria for searching data sources were "risk," "accidents," "human," "technologies," "engineering," and "computer," while the exclusion criteria included "medical." The period for the search was from 2013 to December 2024, with the language set to English only. The search query, detailed below in Table 1, was applied in WOS in December 2024. Then, the secondary qualitative screening was performed to conduct a detailed full-text review of articles that passed the initial screening. This screening ensured alignment with the study's objectives by assessing articles for methodological rigor, thematic relevance, and their ability to address the research questions. Studies that focused on tangential aspects of construction safety and risk assessment were excluded. This process refined the dataset, enabling a more focused analysis of trends, risk factors, assessment models, and safety interventions in construction safety research. After applying all inclusion and exclusion criteria, 66 documents were identified during the database

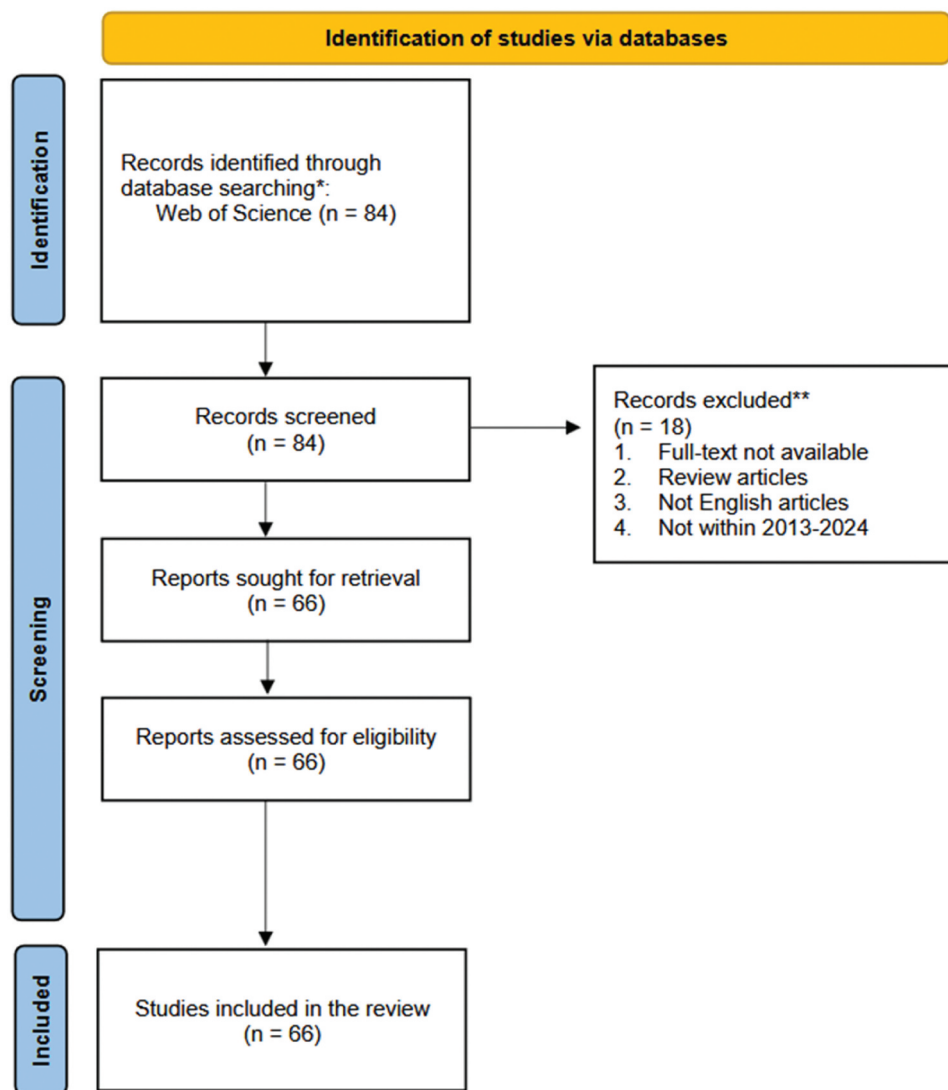


Figure 1. PRISMA flow diagram of the methodology and search results.

Table 1. Search query.

Online database	Search query	No. of results
Web of Science	ALL= (((VR OR virtual reality) OR ((AI OR Artificial Intelligence) AND wearable device)) AND (construction AND safety AND health) AND ((risk OR hazard) AND (assess* OR ident*))) AND PY= (2013–2024) and English (Languages)	66

search. [Figure 1](#) illustrates the PRISMA diagram of the methodology and search results.

3.2. Data analysis

Many current review-based studies on construction safety are conducted in a subjective manner, which may be prone to bias and subjectivity. To address this weakness, a visual map approach has been adopted in this study (Chellappa et al. 2021). In VOS viewer, a visual map was created based on bibliographic data on the following aspects including (1) co-authorship, (2) keyword co-occurrence, (3) citation, and (4) bibliographic coupling. As such, the keyword co-occurrence was

applied. For the keyword co-occurrence analysis, a minimum term frequency threshold of 5 was set, meaning that only keywords appearing at least five times were included. Additionally, similar words with the same meaning were treated as a thesaurus, so variations like “virtual reality,” “virtual-reality,” and “virtual reality (vr)” were summarized into “virtual reality.” In the author co-authorship analysis, the minimum requirement was one document per author, while the author co-citation analysis required a minimum of 50 citations.

Bibliometrics is an interdisciplinary science that integrates linguistics, mathematics, and statistics. The bibliometric analysis attempts to calculate research evolution in various areas and identify

associated trends. This method is usually used to investigate the current research focal point, predict coming research directions, and explore the development of academic research disciplines. Bibliometric analysis has received wide attention from scholars in the last decade. In doing so, the key objectives of this study are as follows: (1) to improve scholars by enhancing their understanding of the setting and scope of research focused on construction occupational safety and health risk assessment according to the bibliometric analysis of published research papers in the WOS Core Collection database, especially emerging and understudied research topics, and (2) to create a groundwork for forthcoming research directions for professionals in the area of construction occupational safety and health risk assessment. A co-citation network gives valuable insight for assessing academic impact and enriches the number of

attentions inclined to researchers. The size of the network nodes indicates the number of authors' publications, as well as the links reflect the internal association between them. The key author group and its collaborative interrelationship in this discipline can be recognised by investigating the structural features of authors and their collaborative networks (Chen et al. 2023).

4. Findings and investigation of results

4.1. RQ1: what are the emerging research trends in subject areas and regions regarding the future application of technological risk assessment in construction?

In the past decade, the adoption of VR technology in construction safety and health risk assessment research has increased, as evidenced by the number

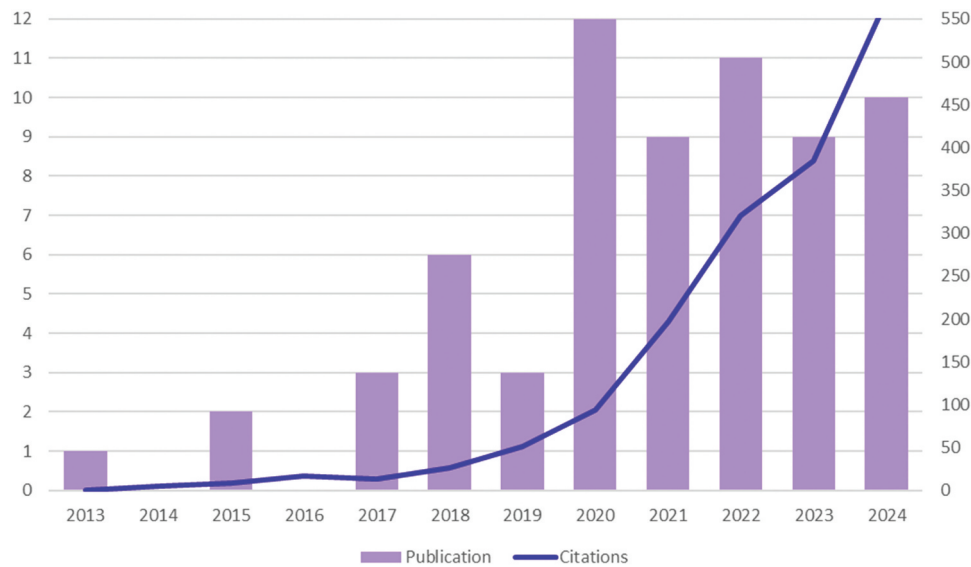


Figure 2. Times cited and publications over time.

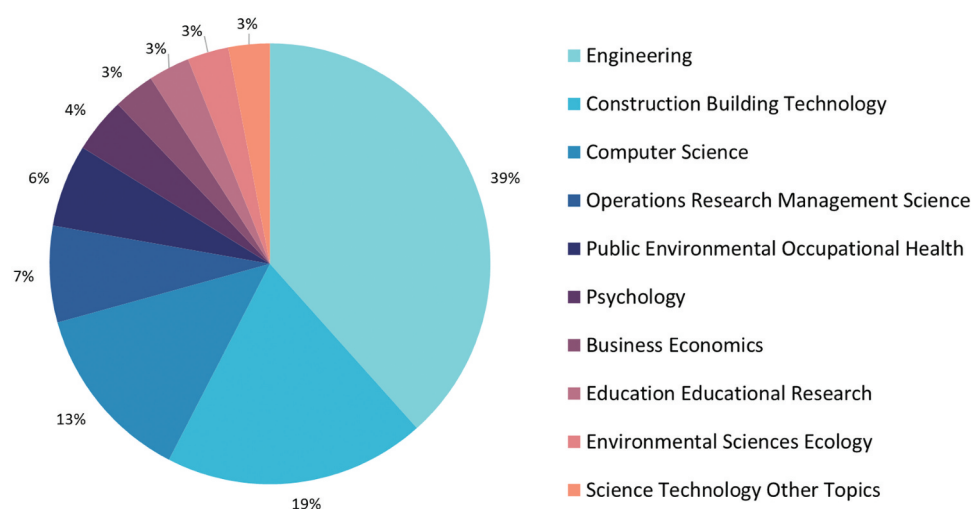


Figure 3. Top 10 subject areas included in publications.

of publications and citations of articles on the WOS. Figure 2 illustrates the total number of related publications and citations from 2013 to Dec 2024. The figure shows exponential growth in citations from 2020 to 2024, reaching nearly 500 citations in 2024. Additionally, it highlights that most papers were published in 2020, with 12 publications released that year.

Figure 3 shows the 10 most popular subject areas. Engineering and Construction Building Technology accounts for the majority of the papers, with 38 and 19 documents, respectively. It is important to note that some published papers may be interdisciplinary, as indicated by the fact that many publications cover multiple topic areas.

The United States has the highest number of publications, followed by China and England, with 25, 9, and 6 publications, respectively, as shown in Table 2. Additionally, the United States leads in citations, followed by South Korea and China, with 842, 243, and 120 citations, respectively.

4.2. RQ2: what is the performance and relationship among academia in the current construction occupational safety and health risk assessment research output?

This section presents the findings of a bibliometric analysis focused on construction safety and health risk assessment using VR, conducted with VOSviewer. Out of the 391 keywords analyzed, 14 met the minimum threshold of five occurrences. The analysis, based on keyword searches, identified three clusters (shown in red, green, and blue in Table 3) that illustrate the relationship between the two topics. In Figure 4a, the size of the circles and letters indicates the frequency of occurrences; keywords that appear more frequently are represented by larger letters and circles. It highlights the clusters within each topic area, revealing that 14 items meet the threshold across the three clusters. Notably, “virtual reality” appears in the red circle,

“construction” in the blue circle, and “health” in the green circle, each with at least five occurrences in the Web of Science database.

Furthermore, Table 3 displays the number of occurrences in each cluster, with the red cluster having the highest total at 75 occurrences. Additionally, the keywords “virtual reality,” “construction safety,” and “health” are the most frequently occurring, with 36, 13, and 13 occurrences, respectively.

Figure 4. visualizes the keyword trends over the years in this study. The terms “risk assessment,” “management,” and “behavior” have been utilized as search terms since 2020. Additionally, the terms “construction safety,” “health,” and “risk” have been frequently used in the past 3 years.

A cluster density map from the author co-authorship analysis is presented in Figure 5a, where authors with close collaborative relationships are grouped into clusters of the same color. This analysis includes 258 authors, each with a minimum of one publication. Gheisari Masoud from the University of Florida leads with eight publications, followed by Eiris Ricardo from Arizona State University and Esmaeili Behzad from Purdue University, each with five. This visualization illustrates the interconnectedness of authors, indicating that those within the same cluster often co-publish. The density of each cluster reflects the strength of these relationships, with denser areas signifying a higher frequency of co-authorship.

The author co-citation analysis, illustrated in Figure 5., includes 30 authors, each with a minimum of 50 citations. The visualization reveals distinct groups of authors, differentiated by color, which indicate the strength of their co-citation relationships. Notably, the top three authors, Puro Vuokko, Kannisto Henriikka, and Lukander Kristian, demonstrate significant interconnectedness in the literature. The spatial arrangement of these clusters reflects the proximity of authors based on shared citations, with authors located closer together indicating a stronger scholarly relationship. This analysis provides valuable insights into the collaborative dynamics and influence within the field.

Table 2. Top 10 countries of publications from 2013 to 2024.

Countries/Regions	Record Count	Citations
United States	25	842
China	9	120
England	6	40
Malaysia	4	45
Spain	4	64
Germany	3	56
Portugal	3	28
South Korea	3	243
Australia	2	24
Denmark	2	68

4.3. RQ3: what are the key technologies and assessment models adopted for construction occupational safety and health risk assessment?

In Table 4, the 10 most-cited sources are arranged by citation number. Le et al.’s (Le et al. 2015) publication had 198 citations, making it the most referenced paper. Meanwhile, the paper by Le et al. (Le et al.

Table 3. Keywords with number of occurrences.

Cluster color	Observable keywords	Number of occurrences
Red	Construction safety, hazard identification, safety training, system, virtual reality, visualization technology	75
Green	Behavior, health, management, workers	34
Blue	Construction, risk, risk assessment, safety	33

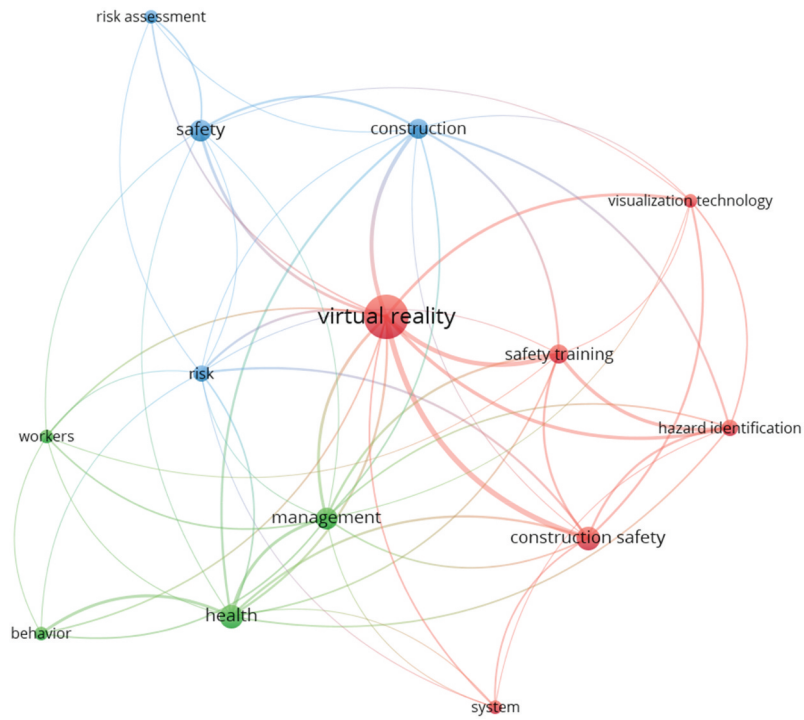


Figure 4. (a) Network visualization showing three clusters in the virtual reality, construction safety, and management. (b) Network visualization of keywords trend.

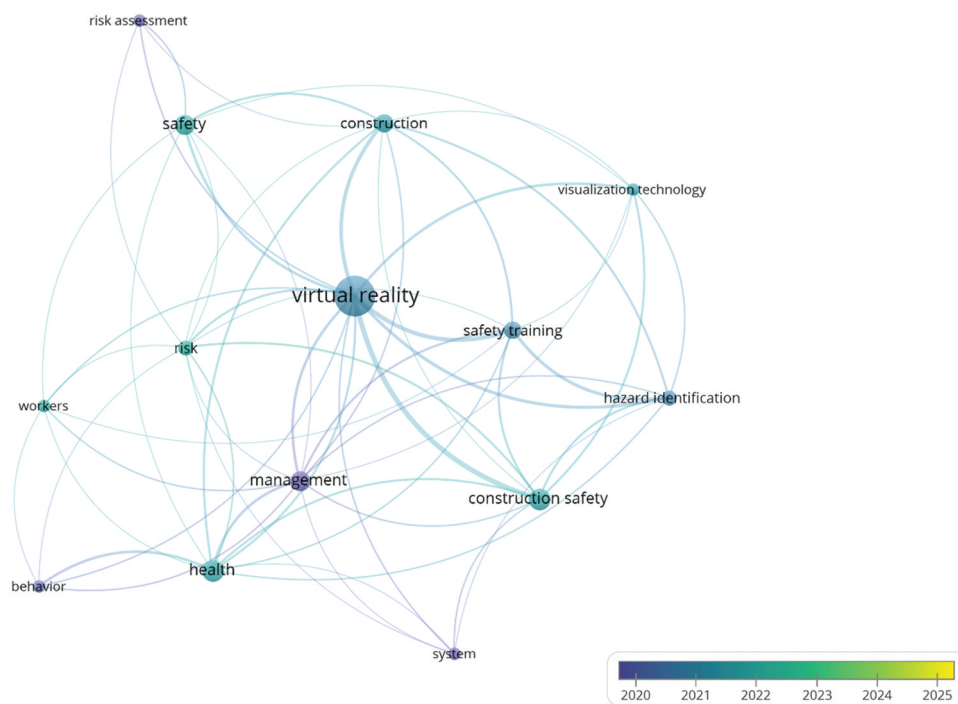


Figure 4. (Continued).

2015) received the most average citations per year, with 18 per year.

Table 5 provides a summary of the keywords and technologies featured in the most-cited publications. Among these terms, “virtual reality” and “construction safety” are the most prominent, aligning with the previously presented network visualization graph. Most studies focus on safety training using virtual reality

approaches, which include immersive virtual reality (IVR) and 360-degree panoramas. For instance, 360-degree panoramas of reality are adopted in safety training to detect potential risks (Eiris et al. 2020). The IVR (Le et al. 2015; Nykänen et al. 2020) and 360-degree panorama (Eiris et al. 2018; Eiris et al. 2020) approaches are also used for the training in construction sites for safety prevention. In addition, the research by Teizer

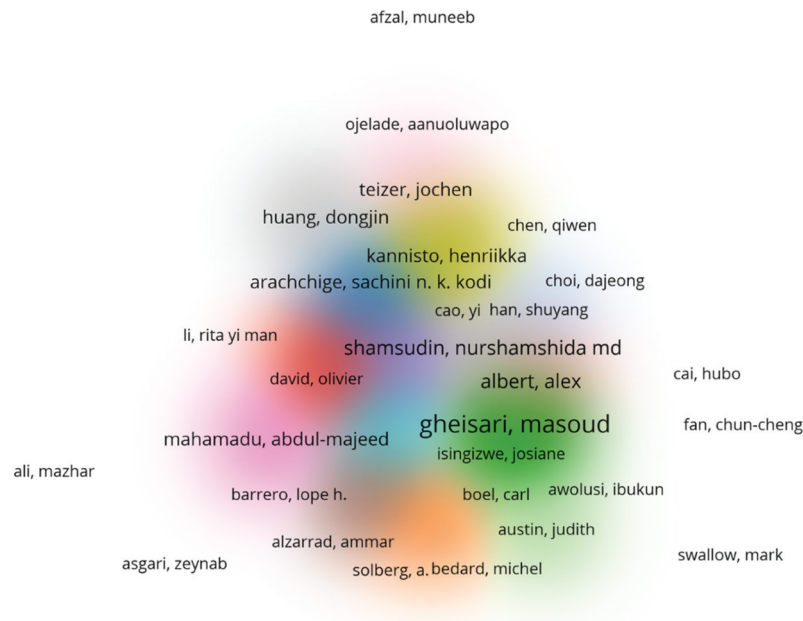


Figure 5. (a) Author co-authorship analysis. (b) Author co-citation analysis.



Figure 5. (Continued).

Table 4. Ten most cited in 2013 to February 2025.

Authors	Source Title	Publication Year	Total Citations	Average per Year
Le et al. (2015)	Journal of Intelligent & Robotic Systems	2015	198	18
Teizer et al. (2013)	Automation in Construction	2013	178	13.69
Eiris et al. (2020)	Automation in Construction	2020	100	16.67
Eiris et al. (2018)	International Journal of Environmental Research and Public Health	2018	97	12.13
Jeelani et al. (2020)	Engineering Construction and Architectural Management	2020	86	14.33
Patel et al. (2022)	Advanced Intelligent Systems	2022	85	17
Nykänen et al. (2020)	Journal of Safety Research	2020	77	12.83
Jeelani and Gheisari (2021)	Safety Science	2021	74	14.8
Eiris et al. (2020)	Safety Science	2020	53	8.83
Ahn et al. (2020)	Advances in Civil Engineering	2020	47	7.83

Table 5. Keywords and technologies used in top 10 citation papers.

Author	Keywords	Technologies
Le et al. (2015)	Safety and health, construction accident, social virtual reality, cooperative learning, inspection game, activity game	Social/collaborative virtual reality (VR) system framework-based construction safety education for experiential learning includes three main modules: Cooperative Distributed Safety Learning (CDSL), Hazard Inspection and Safety Cognition (HISC), and Active Safety Game-based Learning (ASGL).
Teizer et al. (2013)	Education and training effectiveness, cranes and derricks, data visualization and virtual reality, location tracking, safety and health, union ironworker, steel erection	Real-time location tracking data and visualization using ultra wideband (UWB) devices
Eiris et al. (2020)	360-degree panoramas, virtual reality, hazard recognition, construction safety training	Hazard identification training platforms using a 360-degree panorama
Eiris et al. (2018)	360-degree panoramas, augmented panoramas of reality, hazard recognition, construction safety training, virtual reality	Using augmented 360-degree panoramas of reality (PARS) for safety training to enhance hazard identification skills
Jeelani et al. (2020)	Construction safety, safety training, hazard recognition, personalized training, VR	Stereo-panoramic environments using real construction scenes to evaluate trainees' performance; develop a virtual construction site for instructional training
Patel et al. (2022)	Artificial intelligence, connected health, occupational health and safety, occupational risks and hazards, predictive analytics, total worker health	Wearable devices for health monitoring, connected worker solutions for real-time data, and predictive analytics for risk assessment
Nykänen et al. (2020)	Virtual reality, human factors safety training, safety self-efficacy, safety locus of control, safety motivation	Immersive virtual reality (VR)-based safety training program, and apply the holistic human factors perspective in safety training
Jeelani and Gheisari (2021)	Construction safety, UAVs in construction, drones, human-robot interaction, risks of UAVs	Unmanned aerial vehicles (UAVs) for aerial mapping and site monitoring in construction workplaces
Eiris et al. (2020)	Immersive storytelling, 360-degree panorama, safety training, virtual reality	360-degree panorama virtual environments to improve hazard recognition and risk perception
Ahn et al. (2020)	Health, management, behavior, workers	3D building information modeling (BIM) simulation to reflect the hazard condition of the actual site

et al. (2013) used ultra-wideband technology for real-time position monitoring.

Regarding the assessment models, several studies highlight innovative approaches to enhance safety training in construction. Le et al. (2015) present an online social VR system consisting of three modules: Cooperative Distributed Safety Learning (CDSL) for understanding accidents, Hazard Inspection and Safety Cognition (HISC) for applying safety theories, and Active Safety Game-based Learning (ASGL) for practical skill development. The prototype was evaluated using real safety scenarios, demonstrating its effectiveness in improving safety awareness and engagement while identifying both benefits and limitations.

Teizer et al. (2013) integrate real-time location tracking and 3D data visualization into construction worker training for steel-erection tasks. Their assessment model analyzes training session data to enhance safety and productivity for trainers and apprentices, visualizing unsafe practices and indirectly measuring training effectiveness, while also considering return on investment and user feedback.

Eiris et al. (2020) compare VR and 360-degree panorama training platforms for hazard identification, evaluating participants' perceptions of realism and hazard-identification skills. The study found that while students rated the panorama as more realistic, professionals reported no significant difference. However, VR conditions yielded higher Hazard Identification Index (HII) scores, indicating an inverse relationship between perceived presence and HII scores. In another study, Eiris et al. (2018) evaluate an augmented 360-degree panorama training platform aimed at

enhancing workers' hazard-identification skills. A usability test involving 30 participants showed that trainees found the platform beneficial for learning, suggesting its potential to improve safety training and engage workers effectively in hazard recognition.

Jeelani et al. (2020) propose a personalized safety training protocol utilizing stereo-panoramic and virtual environments to boost hazard recognition and management skills. Tested with 53 participants, results indicated a 39% improvement in hazard recognition and a 44% improvement in hazard management, employing realistic scenarios for effective performance assessment and feedback.

Patel et al. (Patel et al. 2022) review emerging smart hardware and software tools that enhance workplace safety, health, and productivity through real-time monitoring and management of occupational risks. Their assessment model discusses various wearable devices for safe lifting, ergonomics, and fatigue management, alongside connected worker platforms that provide contextual decision support, emphasizing the role of predictive analytics in improving safety compliance and resource allocation.

Nykänen et al. (2020) evaluate immersive VR safety training against traditional lecture-based methods and participatory human factor safety training among 119 construction workers. Their findings reveal that VR training significantly enhances safety motivation, self-efficacy, and self-reported safety performance at a one-month follow-up, underscoring VR's potential to improve safety competencies.

Jeelani and Gheisari (2021) examine the health and safety impacts of unmanned aerial vehicles (UAVs) in construction, categorizing potential risks into physical,

attentional, and psychological effects on workers. They propose a two-branch research roadmap for empirically evaluating UAV-related risks and developing regulatory interventions to ensure safe UAV operation alongside human workers.

Eiris et al. (2020) evaluate the effectiveness of immersive storytelling within 360-degree panorama virtual environments for hazard recognition in construction. A pilot study with 40 participants compared this method to traditional OSHA training, finding similar HII scores but significant time savings in training duration, alongside a high sense of presence reported by participants.

Ahn et al. 2020 compare conventional lecture-based safety training with innovative 3D building information modelling (BIM) simulation training at a construction site. Their experiment assessed trainees' understanding, revealing that BIM simulation led to higher comprehension levels. A survey of safety managers further supported the conclusion that virtual reality-based training is more effective than traditional methods, highlighting its lifelike quality, active learning components, and overall enjoyment.

5. Discussion

Construction projects have traditionally relied on standardized safety management methodologies, such as job hazard analysis, pre-task safety planning, and inspection checklists. While these methods have been effective, they often depend heavily on the individual practitioner's ability to identify and respond to hazards, which can be compromised by human factors such as cognitive overload, attentional lapses, and distractions. This review shifts focus from identifying workers who may struggle with hazard management to exploring the benefits and barriers of adopting advanced technologies, particularly wearable sensors and virtual reality (VR), in construction safety and health assessment.

One notable finding of this study is the significant increase in research and development of advanced safety technology post-COVID-19 (Bortoló et al. 2023). The pandemic led to a decline in construction activities globally, creating opportunities to expand research into technologies that mitigate infection risks and enhance the industry's preparedness for future disruptions. This shift has been echoed in numerous influential studies advocating for the integration of innovative technologies in safety management. For instance, VR has shown to enhance training effectiveness by simulating hazardous scenarios, preparing workers for real-life situations (Eiris et al. 2018, 2020, 2020). Such findings can inform the development of tailored VR training modules that address specific construction safety challenges.

The pandemic has also accelerated the adoption of technologies enabling remote participation, particularly relevant for the labor-intensive construction industry (Elrefaey et al. 2022). Advanced technologies not only mitigate infection risks but also prepare the industry for global disruptions. By enabling workers to perform dangerous tasks in a simulated environment, these technologies reduce the likelihood of accidents and improve overall safety performance.

Furthermore, integrating Engineering and Construction Building Technology (ECBT) with VR systems has shown promise in creating risk-free environments for training and operations. Future research can explore the long-term impacts of VR training on actual workplace safety metrics, providing empirical evidence that can guide the development of standardized training protocols. The influential work of Le et al. (2015) on social VR frameworks has further emphasized the importance of experiential learning, demonstrating how collaborative environments enhance safety education. Additionally, VR has emerged as a major tool for construction safety, offering immersive training environments and real-time risk communication capabilities (Alzarrad 2024). This trend highlights the growing recognition of VR's potential to address the limitations of traditional safety methods and foster a safer work environment.

The integration of the Analytic Hierarchy Process (AHP) model with objective parameters, such as BIM risk-related specifications, has further demonstrated the value of advanced technologies in safety management (Aminbakhsh et al. 2013). The application of the AHP model in assessing safety technologies provides practitioners with a structured approach to prioritize investments based on specific project needs. For example, Patel et al. (2022) proposed a model that integrates AHP with real-time data from wearable technologies, illustrating how data-driven insights can inform safety practices. Real-time data collected through wearable sensors and VR systems enhances risk communication and engagement. Augmented reality (AR) allows users to interact with actual objects in computer-generated contexts, facilitating task-driven scenarios or games that enhance user engagement and safety awareness (Akinlolu et al. 2022).

5.1. Limitations and future research

This study has several limitations that provide valuable direction for future research. First, the data sources were limited to journal articles, excluding graduation theses, construction accident reports, and other archival materials. Incorporating these additional sources in future studies could enhance the generalizability and depth of the findings, particularly in understanding real-world applications of advanced safety

technologies. Second, the search criteria were restricted to keywords such as “virtual reality,” “construction,” “safety,” “health,” “risk,” and “hazard,” omitting related terms like “building information modeling,” “digital technology,” “augmented reality,” “accident,” and “incident.” Expanding the scope of keywords in future research could yield new insights and best practices of the field.

Additionally, the study relied solely on the Web of Science database, excluding other prominent databases such as IEEE Xplore, Scopus, and ScienceDirect. Future research should consider incorporating multiple databases for a more robust and inclusive analysis, informing policy-making and regulatory frameworks in construction safety. Furthermore, the study focused exclusively on English-language publications may overlook valuable research in other languages. Expanding to include multilingual sources could enrich the analysis and provide a more global perspective on construction safety challenges.

While advanced technologies such as VR and wearable sensors hold great promise for improving safety in construction, challenges regarding cost, accessibility, and worker acceptance remain. Future research should explore strategies to enhance worker adoption of these technologies, such as comprehensive training emphasizing their benefits. Involving workers in the design and implementation process can foster a sense of ownership and increase acceptance.

Emerging collaborations between academia, industry stakeholders, and technology providers can shape future research directions. Partnerships that bring together VR developers and construction safety experts can lead to tailored training solutions that meet specific industry needs. Financial incentives or subsidies for adopting safety technologies could make them more accessible to smaller construction firms, broadening their implementation.

By addressing these limitations and incorporating insights from influential works, researchers can deepen the understanding of construction safety challenges and foster a culture of safety that prioritizes the well-being of all stakeholders. Advancing technologies and cultivating a proactive safety culture are essential for improving safety outcomes and resilience in the construction industry.

6. Conclusion

This study underscores the transformative potential of advanced technologies including VR in addressing safety challenges within the construction industry. By integrating advanced technologies and immersive tools, the industry can enhance risk communication, improve hazard identification, and create safer work

environments. The findings highlight that traditional safety management methodologies, while foundational, are often limited by their reliance on individual practitioners’ abilities, making them susceptible to human error. Advanced technologies offer a proactive solution by providing real-time data, immersive training platforms, and interactive risk communication tools that empower workers to mitigate hazards effectively.

Despite these advancements, the adoption of advanced technologies in construction safety faces several challenges. Barriers such as cost, accessibility, and worker acceptance must be addressed to ensure widespread implementation. Industry stakeholders need to collaborate on strategies to overcome these barriers, such as investing in affordable technologies, providing training programs, and establishing standardized guidelines for their use. By doing so, the industry can fully leverage the potential of advanced technologies to improve safety outcomes and build a more resilient future.

The findings of this research have significant practical implications for stakeholders in the construction industry regarding the implementation of construction safety and health risk assessment. Construction companies, safety managers, and policymakers should prioritize adopting advanced technologies to enhance safety protocols and training programs. By investing in wearable sensors, AR/VR systems, and real-time data collection tools, stakeholders can foster a culture of safety that prioritizes worker well-being and reduces the likelihood of accidents. Additionally, promoting interdisciplinary collaboration between technology developers and construction professionals can accelerate the implementation of these innovations.

This study demonstrates that the future of construction safety lies in the integration of advanced technologies. By embracing innovation and fostering a proactive safety culture, the industry can tackle its most pressing challenges, improve safety outcomes, and build a more resilient and sustainable future. Stakeholders are encouraged to leverage these findings to drive meaningful change and prioritize the well-being of all construction workers.

Availability of data

The data and materials are available from the corresponding author on request.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Dr. Xiaosheng Su holds a Ph.D. and is an associate professor and young scholar in Bayu, Chongqing. He currently works as a postdoctoral researcher at Southwest Jiaotong University and serves as the director of the Personnel Department at Chongqing Industry Polytechnic College. His research focuses on higher vocational education management and human resource management. To date, he has published one monograph, edited three textbooks, and led five provincial and ministerial projects. His contributions to the field have significantly advanced the understanding and practice of vocational education and human resource strategies in China.

Professor Ka Yin Chau is currently a Professor and Co-Director of Quality Standards and Management at Hang Seng University of Hong Kong. Prior to entering the education industry, Prof Chau worked as a senior manager in a high-tech enterprise for 15 years. Professor Chau holds two patents, has edited four books and published more than 120 academic papers. On 16 September 2024, Professor Chau was selected by Stanford University as one of the top 2% scientists in the world. Professor Chau's research interests are in operations management, sustainability, and artificial intelligence.

Dr. GTS Ho earned his PhD in Industrial and Systems Engineering from the Hong Kong Polytechnic University (PolyU). He has over 20 years of research experience focused on enhancing supply chain performance through technological solutions, leveraging the Internet of Things (IoT), big data analytics, business intelligence, and digital workforce strategies. Dr. Ho has published 130 international journal papers listed in SCI/SSCI. His work garnered over 7850 citations and an h-index of 45 (both excluding self-citations). He was recognized among the World's Top 2% of Scientists by Stanford University in 2021 and was ranked in the top 0.5% of scholars in Expert Systems by ScholarGPS (2022). He currently serves as Associate Editor for both the "International Journal of Engineering Business Management" and the "International Journal of Software Science and Computational Intelligence". Furthermore, Dr. Ho has led numerous ITF and consultancy projects with organizations including MTR Corporation and PCCW Global Limited. Three of his innovative research projects have been recognized with Silver Awards at the International Exhibition of Inventions of Geneva in 2023, 2024 and 2025.

Ms. Ho Tung Yip holds a Master of Public Health degree from The Jockey Club School of Public Health and Primary Care at The Chinese University of Hong Kong and a Bachelor of Engineering degree from The Hong Kong Polytechnic University. Ms. Yip has been actively involved in the advancement of digital health and health technology development, with a particular focus on leveraging innovative technologies to address public health challenges. Her professional expertise also extends to public health counseling and promoting health awareness within communities. She has also contributed to the academic field by publishing several research articles in peer-reviewed journals and authoring a book chapter. Her work highlights her commitment to integrating technology and public health to foster sustainable and impactful solutions for societal well-being.

Dr. Yuk Ming Tang received his B.Sc., M.Phil., and Ph.D. degrees from The Chinese University of Hong Kong (CUHK). Following his graduation, he worked as a Postdoctoral Fellow at the Faculty of Medicine at CUHK. He is currently a Senior

Lecturer in the Department of Industrial and Systems Engineering at the Hong Kong Polytechnic University. Dr. Tang's research interests include Artificial Intelligence (AI), Virtual Reality (VR), the Internet of Things (IoT), Digital Twin technology, blockchain, and sustainable technologies within Industry 4.0, as well as their applications in healthcare. He serves as the Lab-in-Charge and is a key member of several laboratories and Joint Research Centres focused on developing projects involving AI and other advanced technologies. Dr. Tang has published over 80 articles in internationally refereed journals, including numerous contributions to top-ranked publications. He was listed among the world's top 2% scientists in both 2023 and 2024 by Stanford University.

ORCID

Ka Yin Chau  <http://orcid.org/0000-0002-0381-8401>

GTS Ho  <http://orcid.org/0000-0002-8550-4974>

Yuk Ming Tang  <http://orcid.org/0000-0001-8215-4190>

References

- Abdelgawad, M., and A. R. Fayek. 2010. "Risk Management in the Construction Industry Using Combined Fuzzy FMEA and Fuzzy AHP." *Journal of Construction Engineering and Management* 136 (9): 1028–1036.
- Ahn, C. R., Lee S, Sun C, Jebelli H, Yang K, Choi B. 2019. "Wearable Sensing Technology Applications in Construction Safety and Health." *Journal of Construction Engineering and Management* 145 (11): 03119007.
- Ahn, S., Kim, T., Park, Y. J. and Kim, J. M. 2020. "Improving Effectiveness of Safety Training at Construction Worksite Using 3D BIM Simulation." *Advances in Civil Engineering* 2020 (1): 1–12. <https://doi.org/10.1155/2020/2473138>.
- Akanmu, A. 2020. "Musculoskeletal Disorders within the Carpentry Trade: Analysis of Timber Flooring Subtasks." *Engineering, Construction and Architectural Management* 27 (9): 2577–2590.
- Akinlolu, M., Haupt, T. C., Edwards, D. J. and Simpeh, F. 2022. "A Bibliometric Review of the Status and Emerging Research Trends in Construction Safety Management Technologies." *International Journal of Construction Management* 22 (14): 2699–2711.
- Akinosho, T. D., Oyedele, L. O., Bilal, M., Ajayi, A. O., Delgado M. D., Akinade, O. O. and Ahmed, A. A. 2020. "Deep Learning in the Construction Industry: A Review of Present Status and Future Innovations." *Journal of Building Engineering* 32:101827.
- Aladayleh, K. J., and M. J. Aladaileh. 2024. "Applying Analytical Hierarchy Process (AHP) to BIM-Based Risk Management for Optimal Performance in Construction Projects." *Buildings* 14 (11): 3632.
- Albeaino, G., and M. Gheisari. 2021. "Trends, Benefits, and Barriers of Unmanned Aerial Systems in the Construction Industry: A Survey Study in the United States." *Journal of Information Technology in Construction* 26.
- Alzarrad, A. 2024. "Revolutionizing Construction Safety: Introducing a Cutting-Edge Virtual Reality Interactive System for Training US Construction Workers to Mitigate Fall Hazards." *Frontiers in Built Environment* 10:1320175.
- Aminbakhsh, S., Gunduz, M. and Sonmez, R. 2013. "Safety Risk Assessment Using Analytic Hierarchy Process (AHP) During Planning and Budgeting of Construction Projects." *Journal of Safety Research* 46:99–105.

- Analysis, S. F. R. 2021. "What is the Society for Risk Analysis?" Accessed September 5, 2023, from <https://www.sra.org/>.
- Bimpas, A., Violos, J., Leivadetas, A. and Varlamis, I. 2024. "Leveraging Pervasive Computing for Ambient Intelligence: A Survey on Recent Advancements, Applications and Open Challenges." *Computer Networks* 239:110156.
- Bortoló, G. M., et al. 2023. "Sustainable, Technological, and Innovative Challenges Post COVID-19 in Health, Economy, and Education Sectors." *Technological Forecasting and Social Change* 190:122424.
- Chellappa, V., Srivastava, V. and Salve, U. R. 2021. "A Systematic Review of Construction workers' Health and Safety Research in India." *Journal of Engineering, Design and Technology* 19:1488–1504.
- Chen, Q., Zhang, H., Lau, Y. Y., Wang, T., Wang, W. and Zhang, G. 2023. "Climate Change, Carbon Peaks, and Carbon Neutralization: A Bibliometric Study from 2006 to 2023." *Sustainability* 15:5723.
- Cherian, D., and J.-H. Choi. 2020. "A Review of Research on Particulate Matter Pollution in the Construction Industry." *Journal of Cleaner Production* 254:120077.
- Chetty, D. R. V., Boojhawon, R., Bhagwant, S. and Levy, L. 2024. "Factors Affecting the Occupational Safety and Health of Small and Medium Enterprises in the Construction Sector of Mauritius." *Social Sciences & Humanities Open* 10:100964.
- Dey, P., Tabucanon, M. T. and Ogunlana, S. O. 1994. "Planning for Project Control Through Risk Analysis: A Petroleum Pipeline-Laying Project." *International Journal of Project Management* 12 (1): 23–33.
- Du, J., Zou, Z., Shi, Y. and Zhao, D. 2018. "Zero Latency: Real-Time Synchronization of BIM Data in Virtual Reality for Collaborative Decision-Making." *Automation in Construction* 85:51–64.
- Eiris, R., et al. 2020a. "Desktop-Based Safety Training Using 360-Degree Panorama and Static Virtual Reality Techniques: A Comparative Experimental Study." *Automation in Construction* 109:102969.
- Eiris, R., et al. 2020b. "Safety Immersive Storytelling Using Narrated 360-Degree Panoramas: A Fall Hazard Training within the Electrical Trade Context." *Safety Science* 127.
- Eiris, R., Gheisari, M. and Esmaeili, B. 2018. "PARS: Using Augmented 360-Degree Panoramas of Reality for Construction Safety Training." *International Journal of Environmental Research* 15 (11).
- Elrefaey, O., Ahmed, S., Ahmad, I. and El-Sayegh, S. 2022. "Impacts of COVID-19 on the Use of Digital Technology in Construction Projects in the UAE." *Buildings* 12 (4): 489.
- Fargnoli, M., and M. Lombardi. 2020. "Building Information Modelling (BIM) to Enhance Occupational Safety in Construction Activities: Research Trends Emerging from One Decade of Studies." *Buildings* 10:98.
- Geda, M. W., Y. M. Tang, and C. K. M. Lee. 2024. "Applications of Artificial Intelligence in Orthopaedic Surgery: A Systematic Review and Meta-Analysis." *Engineering Applications of Artificial Intelligence* 133:108326.
- Gheisari, M., and B. Esmaeili. 2019. "Applications and Requirements of Unmanned Aerial Systems (UASs) for Construction Safety." *Safety Science* 118:230–240.
- Goerlandt, F., and J. Li. 2022. "Forty Years of Risk Analysis: A Scientometric Overview." *Risk Analysis* 42 (10): 2253–2274.
- Gul, M., Lo, H. W. and Yucesan, M. 2021. "Fermatean Fuzzy TOPSIS-Based Approach for Occupational Risk Assessment in Manufacturing." *Complex and Intelligent Systems* 7 (5): 2635–2653.
- Hamidah, M., Hasmadi, I. M., Chua, L. S. L., Yong, W. S. Y., Lau, K. H., Faridah-Hanum, I. and Pakhriazad, H. Z. 2022. "Development of a Protocol for Malaysian Important Plant Areas Criterion Weights Using Multi-Criteria Decision Making-Analytical Hierarchy Process (MCDM-AHP)." *Global Ecology and Conservation* 34:e02033.
- Hashiguchi, N., Kodama, K., Lim, Y., Che, C., Kuroishi, S., Miyazaki, Y., Kobayashi, T., Kitahara, S. and Tateyama, K. 2020. "Practical Judgment of Workload Based on Physical Activity, Work Conditions, and Worker's Age in Construction Site." *Sensors* 20 (13).
- Hill, J., et al. (2019). "Comparing Apples to Oranges and Other Misrepresentations of the Risk Screening Tools FISK and AS-ISK – a Rebuttal of Marcot Et Al. (2019)."
- Hossen, M. M., et al. 2015. "Construction Schedule Delay Risk Assessment by Using Combined AHP-RII Methodology for an International NPP Project." *Nuclear Engineering and Technology* 47 (3): 362–379.
- Ilbahar, E., et al. 2018. "A Novel Approach to Risk Assessment for Occupational Health and Safety Using Pythagorean Fuzzy AHP & Fuzzy Inference System." *Safety Science* 103:124–136.
- Jebelli, H., Choi, B. and Lee, S. 2019. "Application of Wearable Biosensors to Construction Sites. I: Assessing Workers' Stress." *Journal of Construction Engineering and Management* 145 (12): 04019079.
- Jeelani, I., and M. Gheisari. 2021. "Safety Challenges of UAV Integration in Construction: Conceptual Analysis and Future Research Roadmap." *Safety Science* 144.
- Jeelani, I., Han, K. and Albert, A. 2020. "Development of Virtual Reality and Stereo-Panoramic Environments for Construction Safety Training." *Engineering, Construction and Architectural Management* 27 (8): 1853–1876.
- Kang, H., Sung, S., Hong, J., Jung, S., Hong, T., Park, H. S. and Lee, D. E. 2021. "Development of a Real-Time Automated Monitoring System for Managing the Hazardous Environmental Pollutants at the Construction Site." *Journal of Hazardous Materials* 402:123483.
- Karaz, M., Teixeira, J. C. and Rahla, K. M. 2020. "Construction and Demolition Waste—A Shift Toward Lean Construction and Building Information Model." 51–58.
- Khosravi, M., Sarvari, H., Chan, D. W., Cristofaro, M. and Chen, Z. 2020. "Determining and Assessing the Risks of Commercial and Recreational Complex Building Projects in Developing Countries: A Survey of Experts in Iran." *Journal of Facilities Management* 18 (3): 259–282.
- Koryárová, J., and V. Hromádka. 2021. "Risk Assessment of Large-Scale Infrastructure Projects—Assumptions and Context." *Applied Sciences* 11 (1): 109.
- Kumar, R., et al. 2021. "Understanding Relationship Between Risks and Claims for Assessing Risks with Project Data." *Engineering, Construction and Architectural Management* 28 (4): 1014–1037.
- Kwok, C. P., and Y. M. Tang. 2023. "A Fuzzy MCDM Approach to Support Customer-Centric Innovation in Virtual Reality (VR) Metaverse Headset Design." *Advanced Engineering Informatics* 56:101910.
- Le, Q. T., Pedro, A. and Park, C. S. 2015. "A Social Virtual Reality Based Construction Safety Education System for Experiential Learning." *Journal of Intelligent and Robotic Systems* 79 (3): 487–506.
- Leong, S. C., Tang, Y. M., Toh, F. M. and Fong, K. N. 2022. "Examining the Effectiveness of Virtual, Augmented, and Mixed Reality (VAMR) Therapy for Upper Limb Recovery and Activities of Daily Living in Stroke Patients: A Systematic Review and Meta-Analysis." *Journal of Neuroengineering and Rehabilitation* 19 (1): 93.

- Li, T., Chen, Q., Xi, Y. and Lau, Y. Y. 2023. "A 40-Year Bibliometric Analysis of Maritime English Research: Insights and Implications." *Sustainability* 15 (5): 4348.
- Muñoz-La Rivera, F., Mora-Serrano, J. and Oñate, E. 2021. "Factors Influencing Safety on Construction Projects (Fscps): Types and Categories." *International Journal of Environmental Research and Public Health* 18 (20): 10884.
- Nykänen, M., Puro, V., Tiikkaja, M., Kannisto, H., Lantto, E., Simpura, F., Uusitalo, J., Lukander, K., Räsänen, T., Heikkilä, T. and Teperi, A. M. 2020. "Implementing and Evaluating Novel Safety Training Methods for Construction Sector Workers: Results of a Randomized Controlled Trial." *Journal of Safety Research* 75:205–221.
- Panuwatwanich, K., Roongrisoothiwong, N., Petcharayuthapant, K., Dummanonda, S. and Mohamed, S. 2020. "Ambient Intelligence to Improve Construction Site Safety: Case of High-Rise Building in Thailand." *International Journal of Environmental Research and Public Health* 17:8124.
- Patel, V., Chesmore, A., Legner, C. M. and Pandey, S. 2022. "Trends in Workplace Wearable Technologies and Connected-Worker Solutions for Next-Generation Occupational Safety, Health, and Productivity." *Advanced Intelligent Systems* 4 (1).
- Piroozfar, P., Farr, E. R., Zadeh, A. H., Inacio, S. T., Kilgallon, S. and Jin, R. 2019. "Facilitating Building Information Modelling (BIM) Using Integrated Project Delivery (IPD): A UK Perspective." *Journal of Building Engineering* 26:100907.
- Radianti, J., T. A. Majchrzak, J. Fromm, and I. Wohlgenannt. 2020. "A Systematic Review of Immersive Virtual Reality Applications for Higher Education: Design Elements, Lessons Learned, and Research Agenda." *Computers and Education* 147:103778. <https://doi.org/10.1016/j.compedu.2019.103778>.
- Riggs, J. L., Brown, S. B. and Trueblood, R. P. 1994. "Integration of Technical, Cost, and Schedule Risks in Project Management." *Computers and Operations Research* 21 (5): 521–533.
- Saisandhiya, N. 2020. "Hazard Identification and Risk Assessment in Petrochemical Industry." *International Journal for Research in Applied Science and Engineering Technology* 8:778–783.
- Sami Ur Rehman, M., Thaheem, M. J., Nasir, A. R. and Khan, K. I. A. 2022. "Project Schedule Risk Management Through Building Information Modelling." *International Journal of Construction Management* 22 (8): 1489–1499.
- Sanni-Anibire, M. O., Mahmoud, A. S., Hassanain, M. A. and Salami, B. A. 2020. "A Risk Assessment Approach for Enhancing Construction Safety Performance." *Safety Science* 121:15–29.
- Shafique, M., and M. Rafiq. 2019. "An Overview of Construction Occupational Accidents in Hong Kong: A Recent Trend and Future Perspectives." *Applied Sciences* 9 (10): 2069.
- Shash, A. A., Al-Salti, M., Alshibani, A. and Hadidi, L. 2021. "Predicting Cost Contingency Using Analytical Hierarchy Process and Multi Attribute Utility Theory." *Journal of Engineering, Project, and Production Management* 11 (3): 228.
- Suárez Sánchez, F. A., Peláez, G. I. C. and Alís, J. C. 2017. "Occupational Safety and Health in Construction: A Review of Applications and Trends." *Industrial Health* 55 (3): 210–218.
- Tang, Y. M. 2022. "A Systematic Review of Immersive Technology Applications for Medical Practice and Education-Trends, Application Areas, Recipients, Teaching Contents, Evaluation Methods, and Performance." *Educational Research Review* 35:100429.
- Tang, Y. M. 2025. "A Systematic Review of Abnormal Behaviour Detection and Analysis in Driving Simulators." *Transportation Research. Part F, Traffic Psychology and Behaviour* 109: 897–920.
- Tang, Y. M., W. H. Ip, K. L. Yung, and Z. Bi. 2024. "Industrial Information Integration in Deep Space Exploration and Exploitation: Architecture and Technology." *Journal of Industrial Information Integration* 42:100721.
- Tang, Y. M., Kuo, W. T. and Lee, C. K. M. 2023. "Real-Time Mixed Reality (MR) and Artificial Intelligence (AI) Object Recognition Integration for Digital Twin in Industry 4.0." *Internet of Things* 23:100753.
- Teizer, J., Cheng, T. and 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.
- Toh, S., Wang, H. O. N. G. and Qi, Z. 2023. "Application of Home-Based Wearable Technologies in Physical Rehabilitation for Stroke: A Scoping Review." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* PP:1–1.
- Wang, Q., Wang, H. O. N. G. and Qi, Z. 2016. "An Application of Nonlinear Fuzzy Analytic Hierarchy Process in Safety Evaluation of Coal Mine." *Safety Science* 86:78–87.
- Wu, Y., Zarei, E., Adumene, S. and Beheshti, A. 2019. "Risk Assessment of Electric Vehicle Supply Chain Based on Fuzzy Synthetic Evaluation." *Energy* 182:397–411.
- Xu, W., and T.-K. Wang. 2020. "Dynamic Safety Prewarning Mechanism of Human–Machine–Environment Using Computer Vision." *Engineering, Construction and Architectural Management* 27 (8): 1813–1833.
- Yazdi, M., Zarei, E., Adumene, S. and Beheshti, A. 2024. "Navigating the Power of Artificial Intelligence in Risk Management: A Comparative Analysis." *Safety* 10 (2): 42.
- Yung, K. L., Ho, G. T. S., Tang, Y. M. and Ip, W. H. 2021. "Inventory Classification System in Space Mission Component Replenishment Using Multi-Attribute Fuzzy ABC Classification." *Industrial Management and Data Systems* 121:637–656.
- Yung, K.-L., Tang, Y. M., Ip, W. H. and Kuo, W. T. 2021. "A Systematic Review of Product Design for Space Instrument Innovation, Reliability, and Manufacturing." *Machines* 9 (10): 244.
- Zhang, M., Shi, R. and Yang, Z. 2020. "A Critical Review of Vision-Based Occupational Health and Safety Monitoring of Construction Site Workers." *Safety Science* 126:104658.
- Zheng, G., Zhu, N., Tian, Z., Chen, Y. and Sun, B. 2012. "Application of a Trapezoidal Fuzzy AHP Method for Work Safety Evaluation and Early Warning Rating of Hot and Humid Environments." *Safety Science* 50 (2): 228–239.
- Zhou, Z., Goh, Y. M. and Li, Q. 2015. "Overview and Analysis of Safety Management Studies in the Construction Industry." *Safety Science* 72:337–350.
- Zou, Y., Kiviniemi A., Jones S. W., Walsh J. 2019. "Risk Information Management for Bridges by Integrating Risk Breakdown Structure into 3D/4D BIM." *KSCE Journal of Civil Engineering* 23 (2): 467–480.