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In-depth bibliometric analysis of construction safety risk evaluation

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Subject review

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In-depth bibliometric analysis of construction safety risk evaluation

Scientific and practical risk evaluations play a vital role in quantifying safety risks and promoting the sustainable, long-term development of the construction industry. This paper adopted a bibliometric approach to analyse 322 publications on construction safety risk evaluation published over the past decade, as retrieved from the Web of Science (WoS) database. Using CiteSpace (6.2. R3) for bibliometric analysis, this study presents a panoramic view of the research status in the field of construction safety risk evaluation. It also explores evolutionary trends and existing research gaps, uncovering deficiencies in the field of safety assessment and potential directions for development. This paper suggests a growing emphasis on the application of extended reality (XR), data mining, Internet of Things (IoT) sensors, drones, and building information modelling (BIM), as well as the involvement of multiple stakeholders in the research and application of safety risk evaluation. These findings provide valuable insights for scientific research managers, policymakers, and scholars in this field, ultimately facilitating decision-making, optimising resource allocation, and accelerating the advancement of the discipline.

Key words:
construction safety risk evaluation, CiteSpace analysis, building information modelling (BIM), extended reality (XR), data mining

Pregledni rad

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Dubinska bibliometrijska analiza procjene rizika na radu u građevinarstvu

S ubrzanjem urbanizacije problemi sigurnosti u građevinarstvu sve su učestaliji. Znanstvene i praktične procjene rizika imaju ključnu ulogu u kvantificiranju sigurnosnih rizika i promicanju održivog i dugoročnog razvoja građevinske industrije. Ovaj rad primjenjuje bibliometrijski pristup analizi 322 publikacije o procjeni rizika na radu u građevinarstvu objavljene tijekom proteklog desetljeća, prikupljene iz baze podataka Web of Science (WoS). Primjenom softvera CiteSpace (6.2. R3) za bibliometrijsku analizu studija nudi panoramski pregled istraživanja u području procjene rizika na radu u građevinarstvu. Također se istražuju evolucijski trendovi i postojeće praznine u istraživanju, otkrivajući nedostatke u području procjene sigurnosti i potencijalne smjerove razvoja. Ovaj rad sugerira sve veće težište na primjeni proširene stvarnosti (XR), rudarenja podataka, senzora interneta stvari (IoT), dronova i informacijskog modeliranja gradnje (BIM) te na uključivanje više dionika u istraživanje i primjenu procjene rizika na radu. Ovi nalazi pružaju uvide vrijedne za znanstvene menadžere, donositelje politika i istraživače, olakšavajući donošenje odluka, optimiranje raspodjele resursa i ubrzavanje napretka discipline.

Ključne riječi:
procjena rizika na radu u građevinarstvu, analiza CiteSpace, modeliranje informacija o zgradama (BIM), proširena stvarnost (XR), rudarenje podataka

1. Introduction

Driven by the rapid urbanisation of rural areas, demographic growth, and shifting household structures, coupled with efforts to stimulate economic development through urban redevelopment and infrastructure expansion, the construction of residential buildings has accelerated significantly, particularly in the case of high-rise residential buildings. Although the construction industry has contributed significantly to rapid GDP growth, it has also posed serious safety challenges. According to the Occupational Safety and Health Administration (OSHA), 20.5 % of all fatal workplace accidents occur at construction sites [1]. Based on the frequency of occurrence, construction accidents are referred to as the 'fatal four,' because they happen more often. The 'fatal four' hazards identified by the OSHA include falls, electrical exposure, being struck by objects, and being caught in or between hazards [2]. Additionally, many studies have found that the most common types of accidents at construction sites are falls and collapses [3].

Risk assessment is the process of identifying, analysing, and evaluating potential risks, with the aim of providing a basis for decision-making to effectively manage and reduce risks [4]. Common risk assessment methods include qualitative assessment (such as safety checklists and brainstorming methods), quantitative assessment (such as probability analysis and simulation methods), and comprehensive assessment (such as the fuzzy comprehensive evaluation method and analytic hierarchy process). These methods can be flexibly selected and applied according to specific situations [5-7]. Currently, managing safety risks related to construction remains challenging.

As illustrated in Figure 1, China recorded 5301 fatal accidents associated with construction from to 2017–2024, which caused a loss of 6012 lives. Although the number of fatal accidents has decreased over the past three years, the absolute number of total fatal accidents remains high, indicating that managing construction safety risks remains challenging; hence, construction safety risk evaluation is imminent.

It is difficult to determine which method, qualitative or quantitative, is superior for risk assessment. Therefore, it is crucial to review articles on construction safety risk evaluation methods published over the past decade to explore the current research status and future research trends. Some scholars have summarised multicriteria decision-making methods (MCDM) for assessing occupational safety risks, whereas others have investigated the application of fuzzy and analytic hierarchy process methods in construction safety risk evaluation through content analyses of systematic literature reviews published between 2005 and 2017. The application of system nondynamic models in construction safety risk evaluation have also been reviewed. Some researchers have constructed fire risk assessment index systems tailored to high-rise buildings during construction. In this system, the unascertained measurement theory is employed to create a fire risk assessment model specifically for high-rise buildings. However, few researchers have objectively evaluated the literature on construction safety risks and adopted large sample sizes to avoid subjective judgment.

Bibliometric analysis is a research method based on quantitative characteristics and internal relationships. The statistical analysis of bibliometric indicators (such as authors, institutions, keywords, and citation frequencies) of academic papers, patents, books, and other literature reveals the development trends, research hotspots, and research frontiers of disciplines [8]. This method is widely used in fields such as scientometrics, library science, and intelligence sciences. Based on objective data, this study provides evidence for evaluating scientific research, discipline planning, and supporting decision-making. Commonly used software in bibliometric analyses includes CiteSpace, VOSviewer, and BibExcel. These tools can efficiently process literature data and generate visualisation results, helping researchers to quickly grasp the core content and development context of the research field.

This paper is structured as follows: Section one outlines the significance of the research, including the innovations of the paper and its necessity. Section two describes the research steps, including the selection of software and databases, as well as the search and analysis of relevant literature. Section three presents the results of co-authorship, co-term, and co-citation analyses. Section four discusses keyword evolution (2014–2024) in this field. Section five provides a summary of the primary findings, future research directions, and limitations.

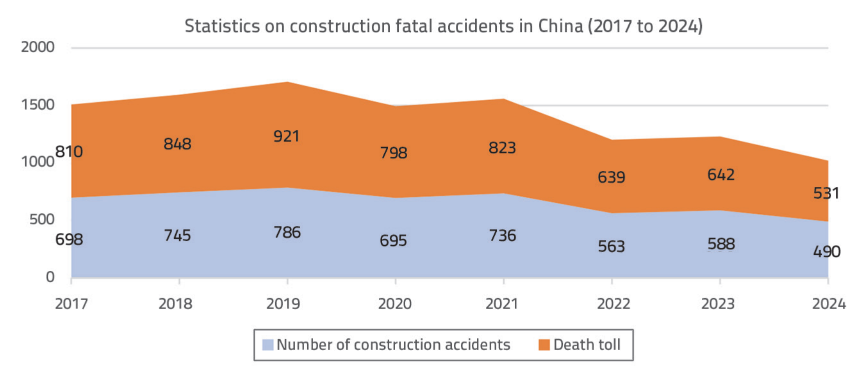

Figure 1. Statistics on construction fatal accidents in China (2017–2024) Data source: Public service portal of the National Engineering Quality and Safety Supervision Information Platform

2. Research methodology

This section systematically discusses the content and processes of this study. The study was guided by a quantitative analysis, with a database information analysis conducted using bibliometric methods. Bibliometric research of the database includes typical co-term and co-citation analyses. Based on co-authorship, co-term, and co-citation analyses, this paper aims to help researchers quantitatively assess the risks associated with the

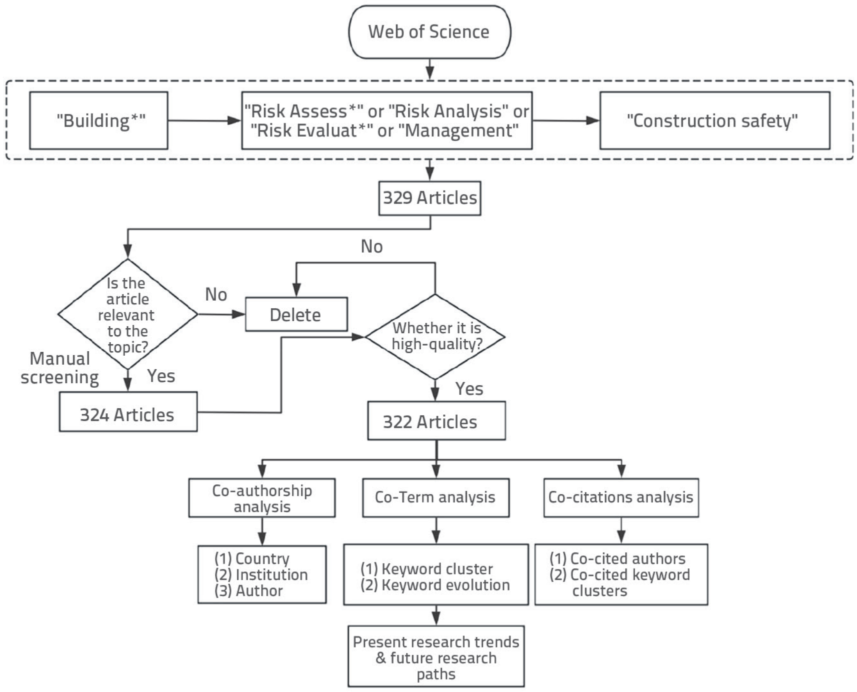

Figure 2. Roadmap of the research methodology

field of construction safety and provide support for a better understanding of current safety risk evaluation methods and emerging research hotspots. As shown in Figure 2, co-authorship analyses were conducted from a macro-to micro-perspective, including country, institution, and author analyses. Co-term analysis involves keyword and keyword evolution analyses. Finally, the co-citation analysis consists of co-cited authors, author co-citation bursts, and co-cited literature analyses.

2.1. Software selection

The CiteSpace analysis software was developed by Professor Chaomei Chen and his team at Drexel University in the United States [9]. This software is specifically designed for bibliometric analysis and has a variety of powerful functions. It can visualise a large amount of literature data, helping researchers intuitively present the structure of scientific knowledge, research hotspots, and evolutionary trends. CiteSpace has several advantages over VoSviewer. CiteSpace is particularly outstanding at tracking the developmental context of disciplines. With its powerful citation analysis function, it can accurately draw a map of the evolution of research hotspots over time, clearly showing the inheritance and breakthroughs of knowledge and enabling researchers to intuitively perceive key turning points and trend directions in the development of disciplines [9]. In addition, when dealing with long-term and complex literature data in specific fields, CiteSpace effectively identify influential key node literature, providing strong support for in-depth research. However, most previous studies have applied VOSviewer for bibliometric analyses. Few researchers have used CiteSpace in the field of construction safety risks. Therefore, this study aims to fill this gap by employing CiteSpace to conduct an up-to-date bibliometric analysis of construction safety risk evaluations.

2.2. Database selection and article screening

Web of Science (WoS), a globally renowned comprehensive academic information resource platform, has collected rich, high-quality academic literature from numerous disciplinary fields. Relying on its powerful citation index function, scholars have presented a complex network of citation relationships in literature, which serves as an important data source for in-depth academic research. Combining WoS with CiteSpace for bibliometric literature analysis offers many remarkable advantages. WoS provides a massive and authoritative data foundation, ensuring the comprehensiveness and reliability of the analysis. However, through various visual charts such as co-citation network maps and co-word network maps, CiteSpace can intuitively present the knowledge structure, evolution of research hotspots, and key node literature within a research field. This helps researchers quickly grasp the research context and trends and discover potential research directions. Taking the field of architecture as an example, in the research on 'green building energy-saving technologies', researchers first used WoS to retrieve relevant literature and obtained a large amount of research data on green building energy-saving technologies. Then, with the assistance of CiteSpace for a co-citation analysis, it was found that a series of papers published by Kibert were frequently cited in numerous studies, establishing a key knowledge node in this field [10]. This indicates the important position of Kibert in the theoretical construction of health and safety [10]. Meanwhile, a co-word analysis revealed high-frequency co-occurring terms such as 'personal protective equipment (PPE)' and 'fall prevention systems, indicating that these represent current research hotspot in the field of health and safety in construction.

This study examines scholarly articles on building construction safety. A manual literature search was conducted using the WoS database. The search query was formulated as follows: (TS = 'Building*' AND TS = ('Risk Assess*' OR 'Risk Analysis' OR 'Risk Evaluat*' OR 'Management') AND TS ='Construction Safety'). To ensure inclusion of the most recent research, only studies published between 2014 and 2024 were considered. Initially, a total of 329 articles were screened. However, because

Table 1 Major journals in construction safety risk evaluation research

No.	Publication Journal	Number of articles	Percentage
1.	Buildings	26	7.90 %
2.	Safety Science	25	7.60 %
3.	Automation in Construction	23	6.99 %
4.	Engineering Construction and Architectural Management	18	5.47 %
5.	Journal of Construction Engineering and Management	17	5.17 %
6.	Sustainability	15	4.56 %
7.	Applied Sciences Basel	7	2.13 %
8.	International Journal of Construction Management	7	2.13 %
9.	International Journal of Occupational Safety and Ergonomics	7	2.13 %
10.	Journal of Civil Engineering and Management	7	2.13 %
11.	Construction Innovation England	6	1.82 %
12.	Advances in Civil Engineering	5	1.52 %
13.	International Journal of Environmental Research and Public Health	5	1.52 %
14.	Journal of Information Technology in Construction	5	1.52 %
15.	Procedia Engineering	5	1.52 %

the retrieval formula did not fully or accurately capture all the relevant studies, five articles unrelated to the theme of the paper were excluded manually. Bibliometric literature retrieval relies heavily on accurate data, including author names, publication titles, abstracts, publication years, and citation details. If any key information is missing, incomplete, or formatted incorrectly in the WoS output, bibliometric software may encounter errors or fail to process the data effectively. To maintain data quality, two more articles with incomplete information were removed manually. Thus, 322 articles were included in subsequent bibliometric analyses.

3. Results and discussion

3.1. Overview of selected publications

3.1.1. Average annual publication

From 2014 to 2024, the number of published papers on construction safety research showed an overall increasing trend, with a notably accelerated growth after 2020, as shown in Figure 3. The number of publications peaked in 2022 (54 papers), followed by slight fluctuations; however, the research interest remained high. Although the overall trend was upward, certain years (2021 and 2023) experienced slight declines, possibly influenced by shifts in research focus, policy adjustments, or unexpected events (such as the COVID-19 pandemic).

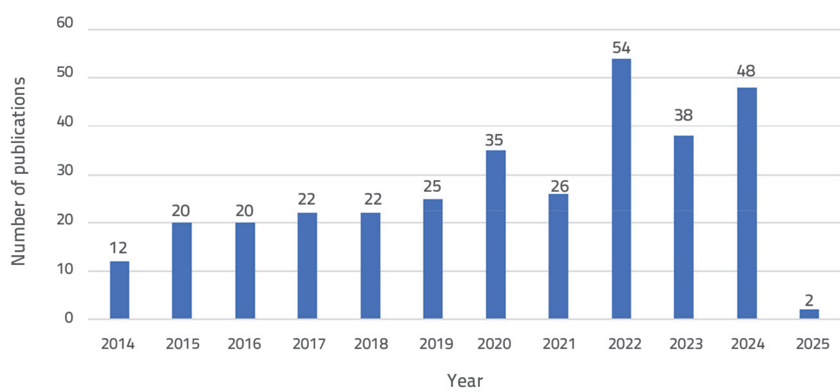

Figure 3. Number of publications per year on construction safety risk evaluation

3.1.2. Major sources

From the perspective of publication volume (Table 1), the top three journals—Buildings, Safety Science, and Automation in Construction—collectively contributed to over 22 % of the total publications, with 26, 25, and 23 papers, respectively. These journals are considered to have high-impact publications. Journals ranked 4th to 6th had fewer publications, but they remain important channels for research on construction safety. Additionally, other journals, despite having fewer publications, still covered related fields such as construction safety, occupational health, and information technology. This indicates that the research outcomes in the field of construction safety are primarily concentrated in high-impact core journals. Researchers should prioritise staying updated with the latest developments in leading publications.

3.2. Co-authorship analysis

Co-authorship analysis is primarily used to study academic collaboration

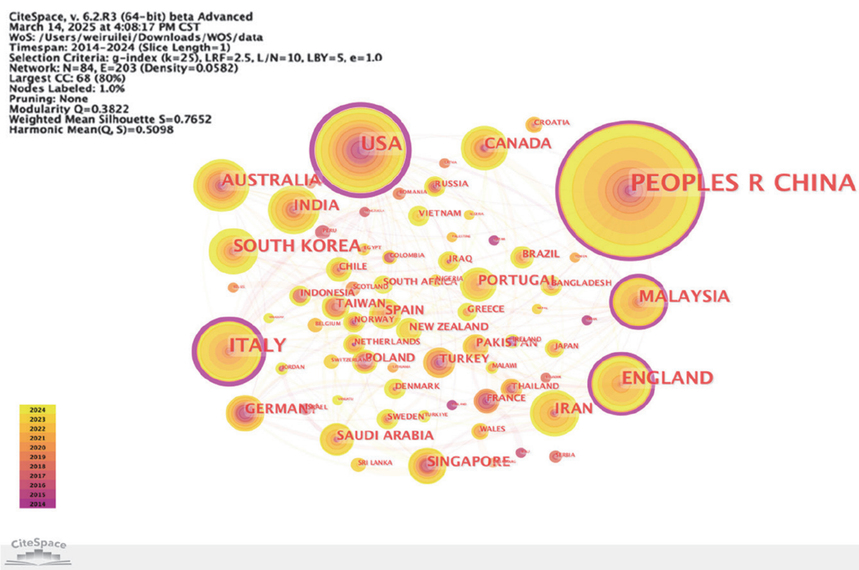

Figure 4. Co-country network in construction safety risk evaluation research

networks and analyse the relationships between authors, institutions, or countries. It typically includes co-author, co-institution, and co-country analyses. Tools such as CiteSpace can be used to create collaborative networks between authors, institutions, or countries. The purpose is to identify core scholars, key institutions, and major countries in the research field to provide a reference for scholars seeking potential collaborators.

3.2.1. Analysis of co-country

Co-country analyses can identify major research countries or regions. The purpose of a co-country analysis is to study the academic collaboration relationships between different countries or regions and identify those that have a significant influence in a specific research field [11]. Figure 4 shows a network of 84 nodes and 203 links containing the primary contributing countries in this field. In the network diagram, the nodes represent different countries, and the size of each node is proportional to the number of publications from each country. The outer purple circle reflects the strength of the betweenness centrality. China has the most publications, followed by the United States, Italy, England, and Australia in decreasing order. The number of studies published in China is 204, far exceeding that in the United States which ranks second. Mediation centrality measures the importance of a node in a network as an 'intermediary' or 'bridge' between other nodes. The United States exhibits the highest centrality, followed by Italy, the United Kingdom, China, and Malaysia. These countries are among the best in terms of international cooperation.

Tables 2 and 3 provide information on the top ten countries in terms of the centrality and frequency of construction safety evaluation research. As shown in Table 2, most of the top-ranked countries are developed or emerging economies, such as the USA, Italy, England, China, Malaysia, Saudi Arabia, and Singapore. These countries usually have a relatively high level of economic development with well-developed construction markets and infrastructure. Therefore, there is an abundance of data and cases from these countries when conducting research on construction risk assessment.

The contributing countries are globally distributed across multiple regions, including North America (the United States and Canada), Europe (Italy and the United Kingdom), and Asia

Table 2. Top 10 countries by centrality in construction safety risk evaluation research

No	Country	Centrality
1.	USA	0,5
2.	Italy	0,25
3.	England	0,16
4.	China	0,13
5.	Malaysia	0,1
6.	Saudi Arabia	0,09
7.	Singapore	0,08
8.	Vietnam	0,08
9.	South Korea	0,07
10.	Iran	0,07

Table 3. Top 10 countries by frequency in construction safety risk evaluation research

No	Country	Frequency
1.	China	204
2.	USA	89
3.	Italy	58
4.	England	44
5.	Australia	38
6.	Malaysia	36
7.	South Korea	34
8.	India	24
9.	Iran	23
10.	Canada	22

(China, Malaysia, Saudi Arabia, Singapore, South Korea, Iran, and Vietnam). This indicates that research on construction risk assessment is of great significance globally and that countries in different regions are conducting relevant studies.

3.2.2. Analysis of co-authors

Co-author analysis using bibliometric methods aims to reveal research cooperation relationships, explore the paths of knowledge dissemination and communication, and evaluate research influences [12]. Co-author analysis helps uncover the central node authors who play an important role in promoting the wide dissemination and exchange of disciplinary knowledge. A co-author network is depicted in Figure 5. This network's threshold value is set to two, consisting of 326 nodes and 201 links, where the size of the nodes represents the publication frequency of each author, and the connecting lines represent the cooperative relationships between the node authors. Several cooperative groups exist in the field of construction risk assessment, concentrated in Patrick Manu and Hamidreza Abbasianjahromi. Many groups came from China, including Li, Huimin, Li, Heng, Tian, Wei, Zhang, and Sijie. Some groups come from other countries, such as Othman, Idris, Skibniewski, Miroslaw, Cheung, Clara Man, and Choudhry Rafiq. They are key figures in the field of construction safety risk and have conducted in-depth research in this field.
The top 20 authors in terms of the frequency of articles in the field of building construction risk are listed in Table 4. The most productive authors are Li Huimin, Othman Idris, and Skibniewski Miroslaw J. Each published five articles on construction safety in the WoS. Following closely is Li Heng and Cheung Clara Man with four articles each. Others have published three articles. Each plays a crucial role in this field of research, demonstrating their commitment to this line of study..

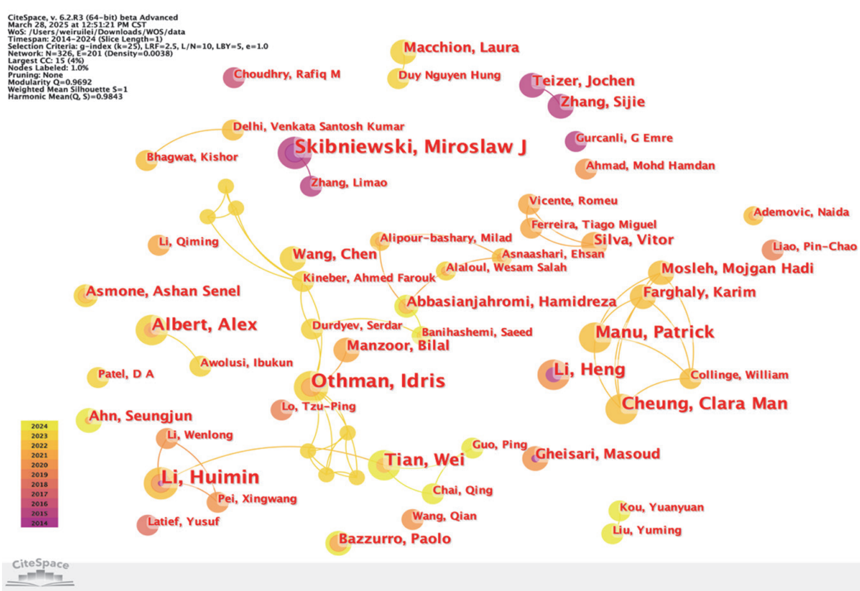

Figure 5. Co-author network in construction safety risk evaluation research

Table 4. Top 20 authors as per frequency in construction safety risk evaluation research

No.	Authors	Frequency
1.	Li, Huimin	5
2.	Othman, Idris	5
3.	Skibniewski, Miroslaw J	5
4.	Li, Heng	4
5.	Cheung, Clara Man	4
6.	Albert, Alex	4
7.	Manu, Patrick	4
8.	Tian, Wei	4
9.	Macchion, Laura	3
10.	Mosleh, Mojgan Hadi	3
11.	Manzoor, Bilal	3
12.	Abbasianjahromi, Hamidreza	3
13.	Zhang, Sijie	3
14.	Silva, Vitor	3
15.	Wang, Chen	3
16.	Ahn, Seungjun	3
17.	Teizer, Jochen	3
18.	Asmone, Ashan Senel	3
19.	Farghaly, Karim	3
20.	Gheisari, Masoud	3

3.3. Co-Term analysis

3.3.1. Analysis of keyword clusters

Keywords can accurately summarise the core content of the literature, facilitating retrieval, classification, and screening, thereby improving search efficiency and relevance. The evolution of keywords not only reflects the core direction of disciplinary development, but also provides empirical evidence for scholars to identify cutting-edge hotspots and optimise research strategies [13].
Figure 6 illustrates the keyword-clustering graph developed using CiteSpace. There are 314 nodes and 512 links representing the current research hotspots. Cluster #0 is associated with 'barriers', which refers to the barriers faced by implementing risk management (RM) in construction sites [14], involving lack of awareness, limited expertise [15, 16], the complexity of analytical tools, and the perceived lack of benefit [17].
Cluster #1 is associated with 'augmented reality (AR)'. Ramos-Hurtado et al. [18]

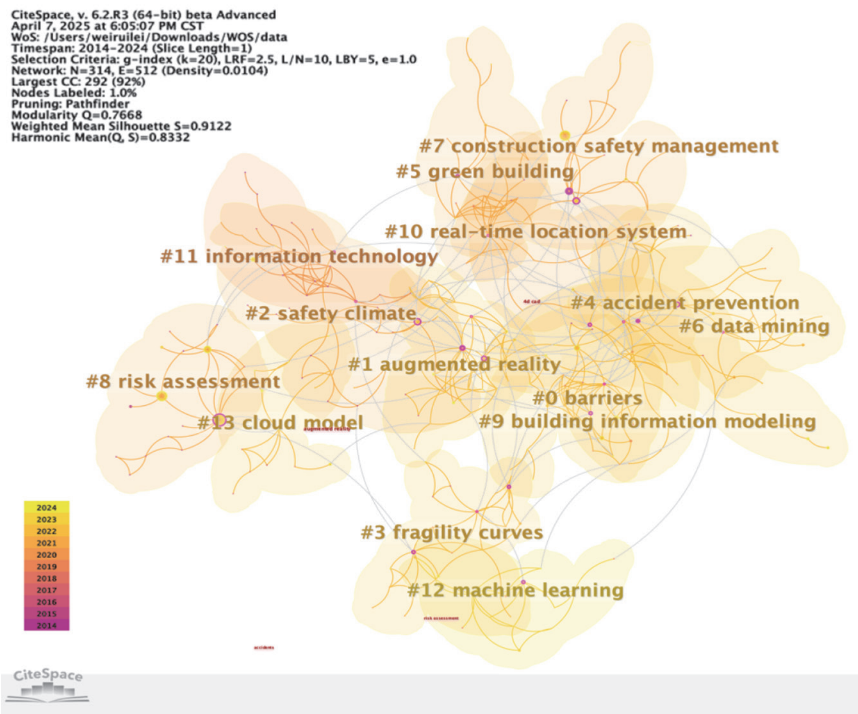

Figure 6. Clustering of keywords in construction safety risk evaluation research

compared key performance indicators (KPIs) between the current inspection and that proposed with AR. KPI is an indicator used to measure the performance of an organisation in achieving predetermined goals. Typical KPIs for construction safety include accident frequency, safety training completion, and PPE compliance rates. Li et al. [19] emphasised the importance of interconnecting the data from AR devices with other tools.

Cluster #2 is associated with 'safety climate', which refers to the shared perceptions and attitudes of employees regarding the importance placed on safety. Li et al. [20] explored safety climate dimensions (SCDs) and safety climate indicators (SCIs) and found that the procedures and policies of safety, co-worker cooperation, and Foreman behaviour were the top three SCIs in China.

Cluster #3 refers to 'fragility curves', which play a critical role in quantifying the probability of structural damage or failure under various hazard conditions. Khalfan et al. [21] offered the potential to use seismic ground motion data to develop empirical fragility curves for non-engineered buildings.

Cluster #4 is associated with 'accident prevention'. Rahayu [22] proposed a quantitative construction safety risk evaluation method based on three indices: likelihood, consequence, and exposure. He addressed the technical challenges of construction hazard prevention through design (CHPTD) by developing plugins that integrate BIM with safety risk data in Autodesk Revit [22].

Cluster #5 is associated with 'green building'. Dewlaney et al. [23] found that leadership in energy and environmental design (LEED) certified building projects exposed industry practitioners to higher safety risks. Fortunato et al. [24] raised similar concerns, as their research also indicated that workers on LEED certified projects were exposed for longer periods to risks such as working at heights, on unstable soils, near electrical currents, and around heavy vehicles and equipment compared to those working on traditional projects.

Cluster #6 is associated with 'data mining'. Due to the large volume and complex structure of safety production data, traditional safety management methods are no longer effective. In 2020, Xia et al. [25] proposed a data mining algorithm with visual data mining techniques and revealed a clear distribution pattern of safety issues during the safety production process in construction enterprises, highlighting the significant relationships between these safety problems.

Clusters #7 and #8 are associated with 'construction safety management' and 'risk assessment', respectively. Risk assessment involves identifying, analysing, and evaluating potential hazards and risks associated with construction activities to determine the likelihood and severity of adverse events. Perlman et al. [26] demonstrated that using a virtual environment helps identify hazards in construction more easily.

Cluster #9 is related to 'building information modelling (BIM)'. Perlman et al. [26] developed plugins which linked BIM with safety risk data for Autodesk Revit and validated that the Revit plug-in can rapidly calculate construction safety risks for various design plans in a short amount of time, demonstrating the significant engineering application value of the developed plug-ins with BIM. Cluster #10 is related to 'real-time location systems'. Arslan et al. [27] proposed using Bluetooth low energy (BLE) beacons to track worker movements and enrich spatio-temporal worker trajectories.

Cluster #11 is associated with 'information technology', which refers to the application of technologies to collect, process, analyse, and share construction-related safety data during construction. Skibniewski et al. [28] found that from 2004 to 2014, a prototype system for the real-time signalling of potential overhead hazards was developed for outdoor automated dynamic tracking applications using UwB technology. Cluster #12 is related to 'machine learning', which involves the utilisation of algorithms and statistical models that enable systems to learn from historical construction safety data, identify patterns and trends related to safety risks, and make predictions for preventing accidents on construction sites. Cluster #13 is a 'cloud model' that refers to a data analysis approach that stores, manages, and processes vast amounts of construction safety-related data in the cloud. Zhang & Qui [29] developed an evaluation index system and incorporated a cloud model for safety assessment. The results of the empirical analysis aligned with the outcomes of the actual project.

3.3.2. Analysis of keyword evolution

Figure 7 depicts the keyword evolution trend from 2014 to 2024. The network threshold value is set at 10. The time linked to each node represents the initial appearance of keywords, whereas the size of a node corresponds to the frequency of the keyword.

In 2014, 'risk management', 'behaviour', 'safety management', and 'accident causation' were the initial research terms; safety management was primarily based on manual inspections, relying on paper records and experiential judgment, which resulted in issues such as data dispersion and delayed responses. Accident causation analyses are mostly based on statistical data and expert experience, lacking systematic modelling. Technical tools, such as BIM, were used only during the design phase.

The research terms BIM, fragility curves, building monitoring, real-time location systems, first occurred in 2016. BIM combined with real-time location systems (RTLS) has been used to construct a smart construction site platform. For example, by tracking personnel locations with RFID tags and integrating them with BIM models, high-risk areas can be dynamically displayed, enabling intelligent management of personnel and equipment. Fragility curves and structural simulation technologies were introduced to quantitatively analyse the failure probability of building components under different loads. For example, finite element models simulate the stress state of steel structure joints, identify weak points, and optimise reinforcement plans. The introduction of RTLS into construction safety management marked the beginning of the transition from traditional safety management models to digitalisation.

In 2018, Bayesian networks provided a probabilistic quantification tool for quantifying complex construction risks, while accident prevention technologies reduced risks through dynamic interventions. Additionally, 4D simulations enhanced safety management efficiency through spatiotemporal visualisation. The introduction of 4D shifted the process of accident post-processing toward proactive safety prevention. By incorporating 4D technology for pre-construction safety training, potential safety hazards could be identified in simulated construction scenarios. Research has shown that virtual simulation of construction scenes identifies more sources of safety incidents than reviewing photos and blueprints. For example, 4D BIM technology, combined with collision detection, can automatically identify conflicts between temporary facilities such as formwork and scaffolding during construction, optimise the construction sequence, and reduce safety hazards caused by design changes.

In 2020, virtual reality (VR) and 3D visualisation technologies enhanced safety training and risk prediction capabilities through immersive experiences and dynamic simulations,

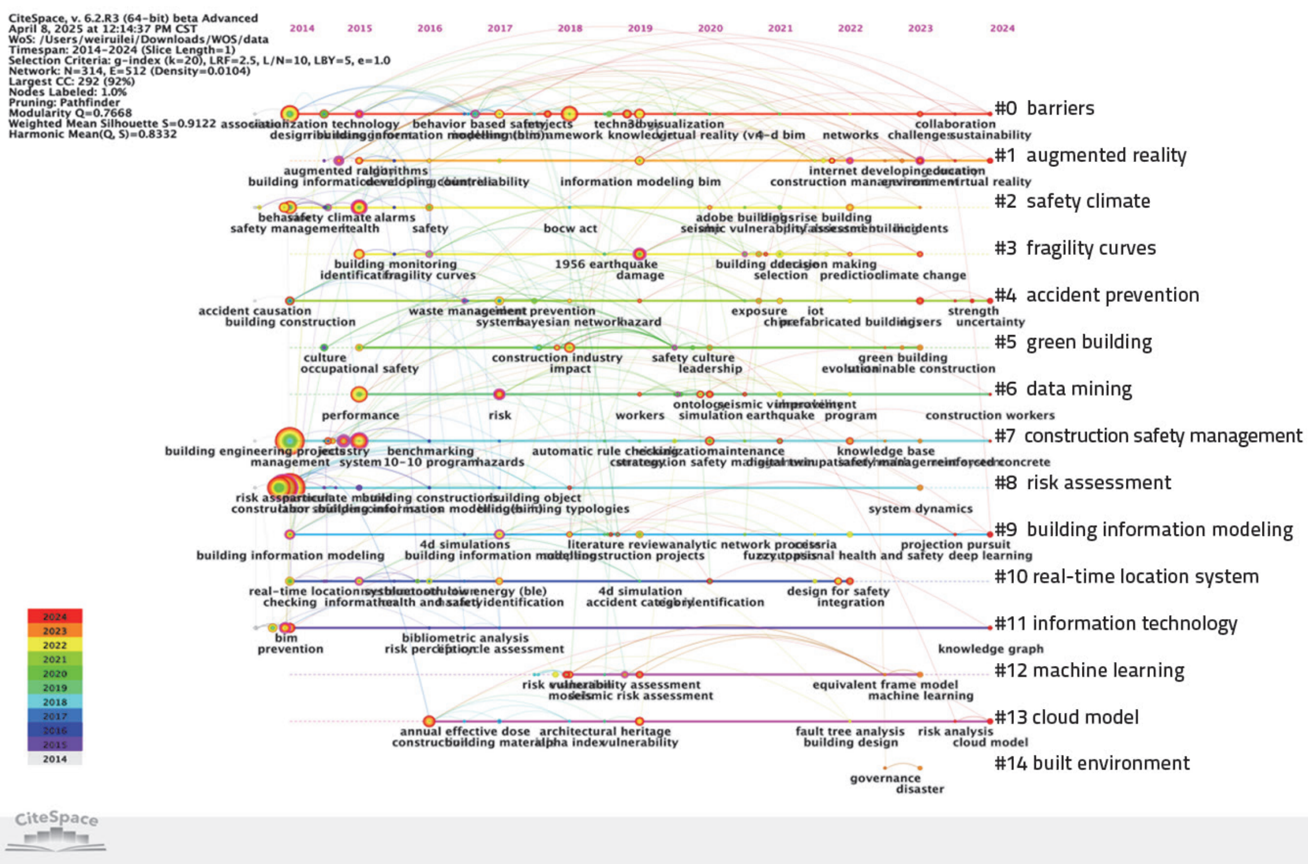

Figure 7. Timeline of keywords in construction safety risk evaluation research

while ANP provided a systematic approach for multi-factor risk assessment in complex construction environments. For example, in high-rise building construction, ANP can be used to quantify indicators such as personnel operations, equipment status, and environmental risks to build a risk evaluation model, determine the weights of various factors, and determine the overall risk level.

In 2022, prefabricated buildings, machine learning, and equivalent frame models were the research hotspots. Machine learning algorithms can extract potential safety patterns and risk factors from data. For example, supervised learning algorithms can be used to develop safety-incident prediction models. By inputting real-time data during the construction process, it is possible to predict and provide early warnings regarding potential safety incidents. The equivalent framework model can predict potential weak points and critical conditions in a structure, thereby guiding the arrangement of reinforcement and support measures during the construction process to ensure the overall safety of the structure during construction.

In 2024, the terms 'knowledge graph', 'deep learning', 'projection pursuit', and 'cloud model' emerged. Knowledge graphs provide structured knowledge support, deep learning enables real-time monitoring and prediction, projection pursuit simplifies complex system analyses, and cloud models enhance dynamic risk assessment capabilities. In future, multitechnology collaboration (such as the integration of knowledge graphs and topological analysis) will further drive the development of safety management toward precision and automation.

3.3.3. Analysis of co-occurring institutions

Figure 8 illustrates a network of co-occurring institutions with a threshold value of two. This network comprises 267 nodes and 178 connections, and the links between the nodes represent

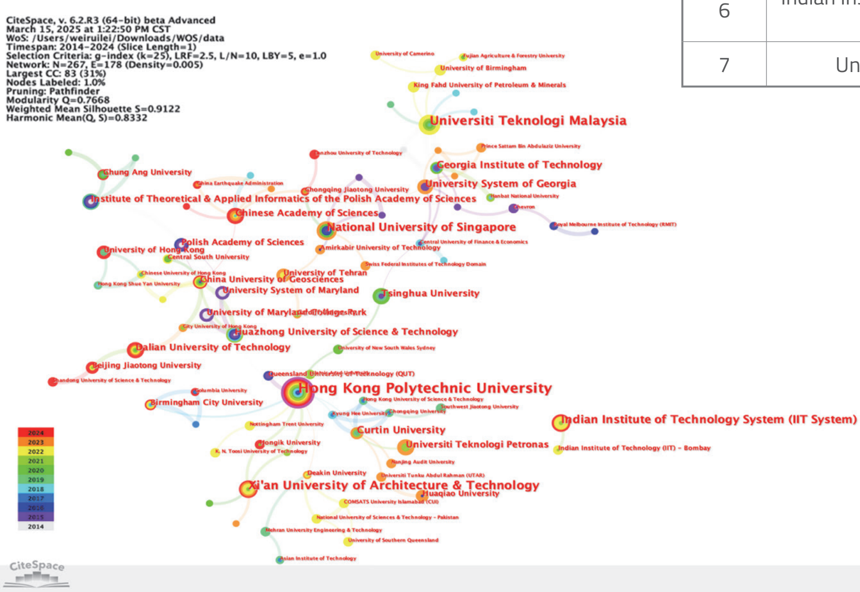

Figure 8. Co-institution network in construction safety risk evaluation research

collaborations between institutions. Most institutions in the network are universities, including Hong Kong Polytechnic University, Universiti Teknologi Malaysia, Xi'an University of Architecture and Technology, National University of Singapore, and China University of Mining and Technology, which serve as network hubs and form several major research communities. For instance, Hong Kong Polytechnic University, Xi'an University of Architecture & Technology, National University of Singapore, and other institutions constitute one of the largest research clusters. Smaller research collaborations are evident, such as that between the Georgia Institute of Technology and University System of Georgia. In addition, approximately 40 institutions have limited external collaboration. Strengthening institutional partnerships is crucial to enhance the dissemination of research expertise.

Table 5 presents the top seven institutions, ranked according to frequency. Hong Kong Polytechnic University has the highest number of publications, followed by Universiti Teknologi Malaysia, Xi'an University of Architecture & Technology, National University of Singapore, and China University of Mining & Technology.

Table 5. Top seven institutions by frequency in construction safety risk evaluation research

No.	Institutions	Frequency
1	Hong Kong Polytechnic University	20
2	Universiti Teknologi Malaysia	14
3	Xi'an University of Architecture & Technology	12
4	National University of Singapore	10
5	China University of Mining & Technology	10
6	Indian Institute of Technology System (IIT System)	9
7	University System of Georgia	7

Table 6 shows the top seven institutions in terms of centrality. Notably, all institutions with a centrality score above 0.05 are based in China and Georgia, including Hong Kong Polytechnic University, Huazhong University of Science & Technology, China University of Geosciences, University System of Georgia, Chinese Academy of Sciences, and Chongqing Jiao Tong University. This highlights their significant contributions to the research in this field, warranting greater recognition and attention.

Table 6. Top seven institutions by centrality in construction safety risk evaluation research

No.	Institutions	Centrality
1	Hong Kong Polytechnic University	0.1
2	Huazhong University of Science & Technology	0.07
3	China University of Geosciences	0.07
4	University System of Georgia	0.06
5	Chinese Academy of Sciences	0.06
6	Chongqing Jiaotong University	0.06
7	Tsinghua University	0.04

3.4. Co-citation analysis

A co-citation relationship is established when two papers are simultaneously cited by a third paper. The co-citation strength (the number of papers that cite both papers) reflects content similarity. Co-citation analyses using CiteSpace software allow the visualisation of the co-citation network between papers and reveal the knowledge base, evolution of research hotspots, and core literature in a research field using methods such as clustering and timeline analyses.

3.4.1. Co-cited authors analysis

In the author co-citation network of CiteSpace software, the nodes represent the frequency of an author's citations, with larger nodes indicating higher citation counts for the author. The thickness of the links represents the co-citation strength between authors, with thicker lines indicating that two authors are co-cited more frequently in the same paper, signifying a stronger association in terms of collaboration or research themes. In Figure 9, the network has 511 nodes and 866 links, which filter out key information about the authors and their relationships. Only a few nodes in the network are of significant importance, indicating that research in the field is concentrated. As shown in Tables 7 and 8, the top five authors based on mediated centrality were Carter, Sacks, Aksorn, Fang, and Goh, whereas the most frequently cited authors were Zhang, Hinze, Ding, Zhou, and Hallowell.

Figure 10 illustrates the top ten authors based on burst intensity. Lu received the most citations, followed by Sulankivi, Gambatese, Carbonari, and Riaz. Additionally, the authors with high burst intensity values included Rozenfeld, Mohammadi, Han, Becerik-Gerber, and Mitropoulos. This indicates that these authors received exceptional attention from the research community during this period because of their publication of influential works, leadership in emerging research trends, and significant contributions to the advancement of the field.

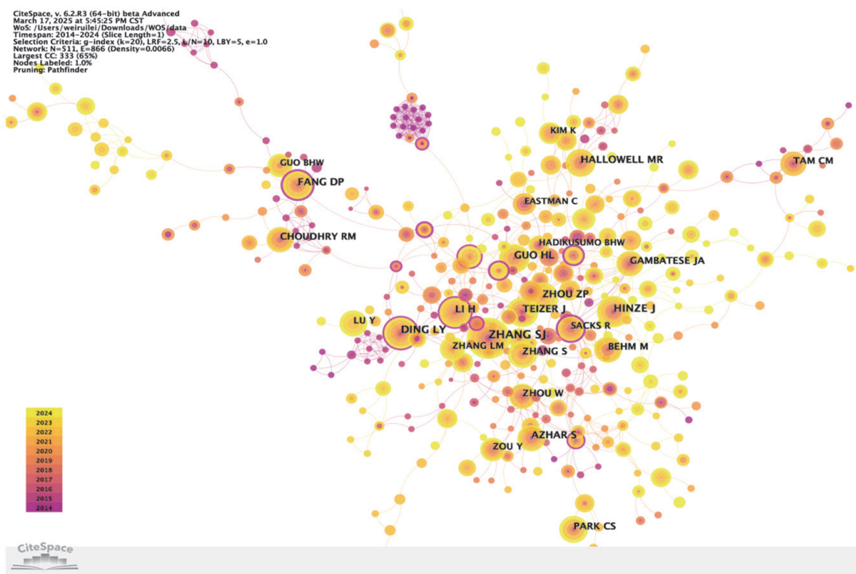

Figure 9. Authors' co-citation network in construction safety risk evaluation research

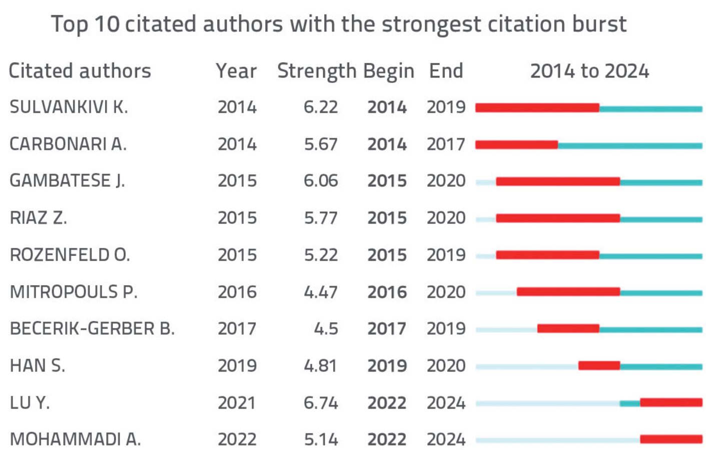

Figure 10 Burst strength of authors' co-citation in construction safety risk evaluation research

Table 7. Ten most frequently co-cited authors by frequency in construction safety risk evaluation research

No.	Frequency	Author
1	98	Zhang Sj
2	70	Hinze J
3	64	Ding Ly
4	60	Zhou Zp
5	57	Hallowell Mr
6	56	Li H
7	55	Teizer J
8	53	Guo Hl
9	52	Fang Dp
10	50	Azhar S

Table 8. Ten most frequently co-cited authors by centrality in construction safety risk evaluation research

No.	Centrality	Author
1	0.37	Carter G
2	0.26	Sacks R
3	0.26	Aksorn T
4	0.24	Fang Dp
5	0.23	Goh Ym
6	0.19	Park J
7	0.17	Ding Ly
8	0.15	Becerik-Gerber B
9	0.12	Moon H
10	0.11	Li H

3.4.2. Analysis of co-cited clusters

The most cited articles in construction safety are listed in Table 9. Zhang et al. [30] developed an automated safety inspection platform by introducing a rule-based engine into BIM. This platform can inform construction project engineers and managers about when and where hazards might occur and what measures can be taken to prevent safety incidents, such as falls from heights, before construction begins. The effectiveness of this platform was validated using real-world case studies. Similarly, Hossain et al. [32] established a structured rule-based knowledge base that focused on design safety. This knowledge base, integrated with BIM, formed an intelligent risk-review system that assists designers in eliminating safety issues during the design phase. The effectiveness of this system was validated using typical case studies.

Yuan et al. [31] developed a program based on algorithmic data extraction and judgment and created a rule-based automated inspection plugin. This plugin integrates BIM and accident prevention through design (PtD) knowledge databases and provides feedback to designers through automatic warning windows. These windows include a construction risk identification ID and corresponding preventive control measure ID from the Revit model, achieving the goal of automatically assessing safety risks during the design phase. Similarly, Lu et al. [35] developed a plug-in that connects BIM with safety risk data in Autodesk Revit; this plug-in can automatically calculate construction safety risks, aiding architects and structural designers in quickly selecting design alternatives.

Zou et al. [33] conducted a review on risk management through BIM and BIM-related technologies, in which they summarised state-of-the-art technologies, including BIM, automated rule checking, knowledge-based systems, reactive IT-based safety systems (such as database technology, VR, 4D CAD, and GIS), and proactive IT-based safety systems (e.g., GPS, RFID, and laser scanning). In conclusion, they suggested that BIM can serve not only as a systematic risk management tool during the development process, but also as a central data generator and platform, enabling other BIM-based tools to perform additional risk analysis.

Malekitabar et al. [34] established a structured framework to demonstrate how object-oriented BIM can be used to classify

Table 9. Ten most frequently cited articles in construction safety risk evaluation research

No.	Frequency	Articles
1.	26	Building information modelling (BIM) and Safety: Automatic safety checking of construction models and schedules [30]
2.	24	Accident prevention through design (PtD): Integration of building information modelling and PtD knowledge base [31]
3.	23	Design-for-safety knowledge library for BIM-integrated safety risk reviews [32]
4.	23	A review of risk management through BIM and BIM-related technologies [33]
5.	17	Construction safety risk drivers: A BIM approach [34]
6.	17	BIM-integrated construction safety risk evaluation at the design stage of building projects [35]
7.	17	Visualization technology-based construction safety management: A review [36]
8.	16	A science mapping approach-based review of construction safety research [37]
9.	16	BIM-based fall hazard identification and prevention in construction safety planning [38]
10.	15	Construction safety planning: Site-specific temporal and spatial information integration [39]

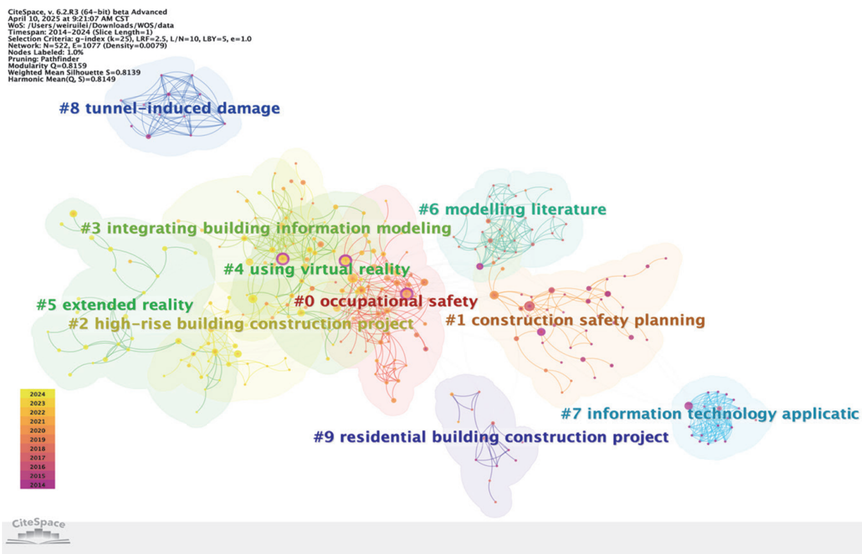

Figure 11. Cluster of co-cited references in construction safety risk evaluation research

the driving factors of accidents, resulting in five sets of drivers: drivers that influence the consequences and probabilities of all kinds of accidents, drivers for the risk of 'fall or falling objects', drivers for the risk of 'unsafe operation', drivers for the risk of 'asphyxiation or cave in', and drivers for the risk of 'electric shock'.

Guo et al. [36] reviewed visualisation technology and found that by supporting safety training, identifying job hazard areas (JHA), and providing onsite safety monitoring and warnings, visualisation technology can enhance safety management. However, certain barriers hindered its widespread application. For example, current location technologies tend to perform effectively only in small areas because of their weak penetration capabilities.

Jin et al. [37] provided an overview of traditional risk management and offered a comprehensive review of recent literature on the latest efforts to manage risk using technologies such as BIM, automated rule checking, knowledge-based systems, and reactive and proactive IT-based safety systems.

Zhang et al. [38] developed a framework that incorporated automated safety rule checking algorithms for BIM. Through a case study, they tested the framework using models from an office and a residential building project in Finland. Their results highlighted the effectiveness of this framework, specifically in simulating fall hazard detection and prevention.

Choe & Leite [39] integrated safety data, including general safety knowledge, site-specific temporal and spatial information from a project schedule, and a 3D model, in a 4D construction safety planning process. They could prioritise risky activities, days, and zones when a project schedule included details regarding the number of workers, occupation types, and zoning plans.

Cluster analysis using CiteSpace and quantitative co-cited references can help identify primary trends in each field and new research directions. CiteSpace provides two metrics: the modularity value (Q value) and average silhouette value (S value). The Q value, which reflects the degree of separation between different clusters in a network, was used to evaluate the significance of the clustering structure. A larger Q value indicates a more significant clustering effect, with Q values exceeding 0.3 considered acceptable. Clustering is considered reasonable when the Q value exceeds 0.5 [40]. The S value reflects the average silhouette coefficient of clusters, and it is used to measure the cohesiveness of nodes within the same cluster and the separation between different clusters. A larger value indicates more reasonable clustering, with S values exceeding 0.5 generally considered acceptable. Figure 11 illustrates a cluster analysis graph as a co-citation reference network with 522 nodes and 1626 links. The cluster analysis results, with Q = 0.732 and S = 0.791, show relatively reliable and clearly structured clustering. Nine clusters were identified.

In CiteSpace, which is a cluster of co-cited reference timelines, the size of a node represents the frequency of co-citations. Figure 12 indicates that nine clusters were cited more frequently within the co-citation network, highlighting their greater influence or importance in the research field. Before 2015, research mainly

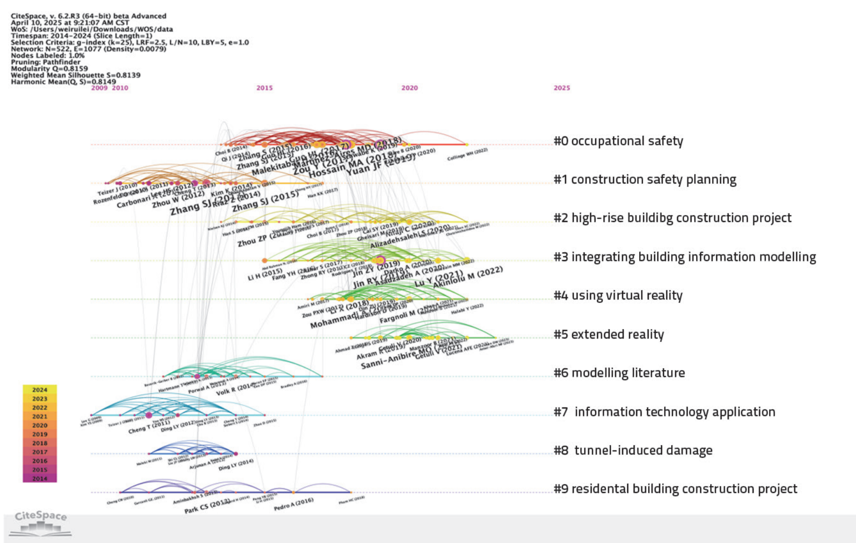

Figure 12. Timeline of co-citation clusters in construction safety risk evaluation research

focused on construction safety planning [41], information technology applications, tunnel-induced damage, and residential buildings, which were mainly distributed among the analysis of accident causes and traditional safety planning based on accident experience. Owing to the development of computer technology, scholars have turned their attention to information technology as it offers innovative solutions, such as real-time monitoring, data analysis, and improved communication, to enhance safety management, prevent accidents, and optimise construction processes.

From 2015 to 2020, scholars mainly focused on high-rise buildings and occupational safety. High-rise building construction involves multiple complex processes, such as construction of foundation, structural erection, and installation of exterior claddings. Each process involves its own set of safety risks. Researchers have paid more attention to occupational safety as it focuses on protecting construction workers from various hazards at work, ensuring their well-being and the smooth progress of construction projects through measures such as training, risk assessment, and regulatory compliance.

After 2015, technologies such as BIM, VR, and XR emerged and developed rapidly between 2015 and 2024. Yap et al. [42] reported that the most effective emerging technologies for safety management include BIM, wearable safety technologies, and robotics and automation (R&A). The implementation of safety technologies in construction projects can steer the industry toward the future of Construction 4.0.

Unlike traditional methodologies that rely on visual inspections using checklists, whose effectiveness depends on the quality of a safety advisor's (SA) inspection, AR serves as a 3D viewer with an intuitive interface for the SA. Consequently, functional requirements are specified, and various information layers and user interfaces for AR applications have been proposed [18].

Rivera et al. [43] reviewed how XR addresses key factors influencing safety in construction projects. XR, which includes VR, AR, and mixed reality (MR) technologies, is used in construction safety management. This paper reviews the literature on XR applications that address safety-critical processes (SCPs) and analyses how these advancements relate to methodologies and technologies in the construction industry, such as BIM. They indicated that among 100 safety-critical process (fSCP) factors, 59 were addressed using XR technologies. These factors are predominantly linked to the 'construction site' and 'materials and equipment' categories. They also revealed that using digital twins of buildings and infrastructure necessitates the use of tools for visualisation and interaction. In this context, XR plays a crucial role.

Getuli et al. [44] applied VR to safety training, bridging the existing knowledge gap on the integration of BIM and VR into real construction projects for safety training by utilising standardised rules that can be widely applied across different projects. They also employed a customised toolkit with a mobile smartphone solution to administer safety-training scenarios, enhancing the portability of construction sites compared with PC-based VR solutions.

XR and BIM have been integrated to improve hazard identification, strengthen safety planning, enhance safety inspections, boost safety monitoring and supervision, and increase safety awareness. Due to technological advancements and convenience, the integration of XR and BIM has become increasingly popular in safety management.

4. Discussion

In the field of construction risk assessment, there have been significant changes in keywords over the past few years, and several new research directions have emerged. Below are the keyword evolution and technological trends (2014–2024) in the field of construction risk assessment, based on what we learned in the previous chapters.

Initially, the application of digital technologies to construction safety was expected to gradually increase over time. However, a keyword evolution analysis from 2014 to 2024 revealed more rapid and multidimensional technological integration than anticipated. For instance, in 2016, the simultaneous emergence of 'BIM', 'fragility curves', and 'RTLS' marked a significant turning point, as safety management began transitioning toward digital platforms. Notably, BIM combined with an RTLS enabled real-time tracking of workers using RFID tags and the visualisation of high-risk zones in 3D models, which greatly enhanced intelligent site management.

In 2018, the appearance of keywords like 'Bayesian networks', 'accident prevention technologies', and '4D simulation' signalled a shift from reactive to proactive safety strategies. Notably, the use of 4D BIM for pre-construction safety training has proven more effective in detecting more potential hazards than traditional blueprint reviews, highlighting the growing importance of spatiotemporal visualisation in hazard identification.

By 2020, immersive technologies such as 'VR' and '3D visualization' have become prevalent, offering a more engaging and effective platform for safety training. Meanwhile, the adoption of 'analytic network process (ANP)' introduced a structured and quantitative approach for assessing complex safety risks, especially in high-rise construction contexts.

Data from 2022 onward reflect an intensified focus on data-driven intelligent systems. 'Machine learning' and 'equivalent frame model' emerged as prominent keywords, indicating a trend toward predictive modelling. For example, supervised learning techniques were applied to real-time data to anticipate and warn against potential safety incidents, and structural simulations using equivalent models were used to guide reinforcement planning.

By 2024, emerging concepts, such as knowledge graphs, deep learning, projection pursuit, and cloud models, marked a significant shift toward intelligent, automated, and systematised risk management. Notably, the fusion of knowledge graphs with deep learning models enables a more holistic, real-time assessment of safety conditions, thereby advancing the field toward data-driven precision and automated construction safety management.

Overall, the bibliometric evolution of keywords reveals not only the accelerated adoption of digital technologies, but also the growing convergence of AI, simulation, and data-driven methodologies in the field of construction safety.

5. Conclusion

This study employed a bibliometric search approach incorporating knowledge graphs and scientometric analyses in CiteSpace, followed by a detailed qualitative discussion to review 322 journal articles in the field of construction safety risk evaluation. The results indicated a growing number of articles on the subject, with the majority published in Buildings, Safety Science, and Automation in Construction. In a co-institutional analysis, Hong Kong Polytechnic University stood out, with both the highest number of publications and centrality.

In the co-authorship analysis, universities were the primary contributors, whereas research laboratories and companies had a relatively smaller impact. Notable collaborations include the Huazhong University of Science & Technology, China University of Geosciences, University System of Georgia, and Chinese Academy of Sciences, all of which have made significant contributions and worked together meaningfully. The most significant contributions come from China, the United States, Italy, the United Kingdom, and Australia, with these countries far outpacing the others in terms of publication output.

Collaborative efforts among authors from various countries have highlighted their joint research endeavours. The United States showed the highest centrality, followed by Italy and the United Kingdom, which are leaders in international collaboration. Although China leads in publication volume, it does not exhibit the highest centrality, suggesting that it could benefit from increased involvement in communication and teamwork.

In the co-term analysis, this study identified key focus areas in the last decade, including 'barriers', 'AR'), 'safety climate', 'data mining', 'accident prevention', and 'green buildings'. Several keywords have a long history in the field but continue to serve as central themes in ongoing research, such as 'safety climate', 'risk assessment', 'construction safety management', 'barriers', and 'accident prevention'. The research frontier is centred on the application of XR, with a growing emphasis on improving the accuracy and interpretability of XR applications while incorporating emerging technologies such as data mining, Internet of Things (IoT) sensors, drones, and BIM.

The analysis also identified the most productive scholars in construction safety risk evaluation based on a selected literature samples, including Zhang, Hinze, and Ding, who were the most frequently cited authors. [30-32] were the most frequently cited articles, underscoring the significant contributions and influence of these studies. Furthermore, a scientometric analysis offered insights into future research directions, including the application of artificial intelligence and data analytics in site monitoring and decision making, facilitating stakeholder collaboration via digital platforms and the integration of BIM and XR into safety planning and training. In future, the research trends may concentrate on the following:

- **Integration of information and communication technologies (ICT) (e.g., BIM and VR) in safety planning.**
  Nurhendi et al. [45] argued that ICT-based frameworks could be further tested with additional real-world cases, evaluating aspects such as user-friendliness, user readiness, acceptance, and ease of safety communication. Further research is required on the interoperability of multiple ICT tools to facilitate information exchange during real-time data collection and processing [37].
- **Integration of artificial intelligence and data analytics in site monitoring and decision making.**
  For instance, AI-powered vision systems can recognise the unsafe behaviour of workers in real-time, and predictive analytics can anticipate equipment breakdowns based on historical data and current operating conditions. Advanced data analytics techniques, such as data mining, statistical analysis, and deep learning, can uncover hidden relationships and trends. In future, domain knowledge is required to ensure that AI models are accurately trained and that the insights generated are relevant and actionable.
- **Cloud model.**
  The integration of cloud models into site safety management is expected to transform the construction industry by enabling smart, real-time, and scalable safety solutions. Cloud-based platforms can collect and analyse large volumes of data from various sources, such as IoT sensors, drones, and worker performance metrics, thereby offering enhanced situational awareness and predictive insights. Choe & Leite [39] proposed a four-dimensional (4D) construction safety planning process that addressed site-specific temporal and spatial safety information integration, offering safety personnel a proactive site-specific safety planning tool that can enhance emergency management governance on site [46]. In future, more real-world cases will be required to test and verify the proposed safety planning process.
- **Promoting stakeholder collaboration through digital platforms.**
  Research should explore solutions based on digital platforms and collaborative technologies (such as BIM and cloud platforms) to enhance stakeholder involvement and information sharing in risk management. This can help create an integrated safety management system that facilitates effective communication and collaboration among stakeholders at all stages of a project, including designers, contractors, suppliers, regulatory agencies, and workers. This will ensure that safety risks are identified and addressed in a timely manner, effectively reducing the likelihood of accidents and driving the entire industry toward a safer, more collaborative, and intelligent future.
- **Shift safety management and risk assessment in planning and design phases.**
  Safety should be addressed during the design stage [47] when hazards can be identified through ontology-based semantic modelling. Zhang et al. [48] developed a framework that incorporated automated safety rule checking algorithms into BIM. This platform included scheduling simulation modelling and the adoption of radio frequency identification (RFID) for site layout modelling, consistent with the approach proposed by Rafique et al. [49]. Additionally, a finite element method for tower-crane stability and rule-checking modules was designed

to identify and eliminate potential fall hazards that might have been unintentionally integrated into the construction schedule early in the planning phase of a project [50]. The commercialisation of BIM needs to be studied further.

- **Transformation of traditional cast-in-place concrete construction into a prefabricated and assembled building type, reducing onsite operations, and minimising onsite safety risks.**
  Abd Razak et al. [51] proposed a design for manufacturing and assembly (DfMA) approach to minimise temporary work in construction sites and reduce reliance on unskilled foreign labour, thereby promoting a safer working environment.

The contribution of this study is lies in its comprehensive integration of state-of-the-art reviews on construction safety risk evaluation from the last decade, and its significance stems from its ability to provide a valuable overview of the current state of research in the field of construction safety.
By analysing and synthesising the latest developments and trends, this study proposes future research directions that can help researchers better understand the key challenges, opportunities, and knowledge gaps in this field. It also offers valuable insights into emerging technologies and their potential applications in this field. This information can be used to guide the development of more effective safety risk evaluation methods and tools, as well as support the implementation of safety measures in construction projects.
This study has some limitations. First, the review is solely based on a literature sample selected from the WoS database, and included only English journal articles. As a result, some latest research published in other languages or formats, such as books and other sources (e.g. Scopus and EI), may have been excluded. In addition, owing to software limitations, different parameter settings may lead to varying analytical results. Future research could employ systematic literature review methods to explore the specific applications of particular construction types or assessment methods in more detail.

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