ISSN 1392-3730 / eISSN 1822-3605

VILNIUS TECH
Vilnius Gediminas Technical University

JOURNAL of CIVIL ENGINEERING and MANAGEMENT

2026
Volume 32
Issue 2
Pages 231–250
https://doi.org/10.3846/jcem.2026.23497

OVERVIEW AND ANALYSIS OF SAFETY MANAGEMENT IN PREFABRICATED CONSTRUCTION (2012–2022)

Clyde Zhengdao LI[1]✉, Qingyi YU[1], Vivian W.Y. TAM[2], Hengqin WU[1]

[1] *Sino-Australia Joint Research Center in BIM and Smart Construction, College of Civil and Transportation Engineering, Shenzhen University, Shenzhen 518060, China*
[2] *School of Built Environment, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia*

Article History:
- received 22 May 2023
- accepted 28 October 2024

Abstract. The stable development of the construction industry plays a significant role in national economic growth. With the continuous reform and progress of the construction industry, construction safety has become a vital issue of concern and emphasis. As an essential means for the sustainable development of the construction industry and industrialization of construction, prefabrication has the advantages of reducing waste of resources and improving construction safety and efficiency and is strongly promoted by the construction industry around the world. Although the safety management of traditional construction has been fully researched, the traditional safety management mode cannot be directly applied to assembled construction because of differences in their construction characteristics and management scopes. Thus, investigating the safety issues of prefabrication is necessary. Although numerous scholars analyzed safety in the different construction stages of assembled buildings, many connections and contents in the literature must be summarized, and systematic literature research must be conducted. Therefore, this study uses a systematic and comprehensive review approach to fill the research gaps. In the first stage, 107 papers related to prefabrication safety management published, meeting the requirements are selected through a literature search. In the second stage, scientometric analysis is conducted to identify the journal sources, scholars, regions, and keywords. In the final stage, content analysis is performed to achieve three main objectives: 1) to identify the differences between prefabricated and conventional buildings and summarize the characteristics of prefabricated buildings (PBs) to obtain the characteristics of prefabrication safety management, 2) to summarize the research topics, and 3) to discuss and provide signposts for potential research directions. This study provides a comprehensive knowledge framework that links current research areas with future research trends, thereby providing a multidisciplinary guide to researchers to gain insights from the latest research on prefabrication safety management.

Keywords: prefabrication, safety management, scientometric analysis, science mapping, literature review.

✉Corresponding author. E-mail: *clyde.zhengdao.li@szu.edu.cn*

1. Introduction

The construction industry provides employment to over 100 million people around the world and contributes 6% of the global GDP. Therefore, ensuring stable growth in the construction industry is crucial for national and global economic development. However, the industry has been facing significant challenges regarding work health and safety, with the occurrence of frequent accidents and fatalities. In Mainland China, the "Circular of the General Office of the Ministry of Housing and Urban-Rural Development on the Production Safety Accidents of Municipal Housing Engineering in 2019" revealed a total number of 773 safety production accidents in municipal engineering, leading to more than 900 fatalities (Ministry of Housing and Urban-Rural Development, 2019). In Hong Kong, according to Hong Kong Labour Department data, the construction industry recorded 26.1 accidents per 1,000 workers in 2020, whereas the manufacturing industry recorded 12.5 accidents per 1,000 workers for the same period (Hong Kong Labour Department, 2020). Therefore, the safety issue in the construction industry remains extremely important.

Prefabricated construction was proposed as a substitute construction approach, which involves assembling structures using components that were factory produced, then transported to the building location (Song et al., 2022a). This method has been praised for its advantages in terms of project duration, safety performance, and project quality (Li et al., 2021). For instance, in Mainland China, the State Council of China set a target for prefabricated buildings (PBs) to comprise 30% of new buildings by 2026.

However, compared with the construction mode of traditional buildings, PBs, as a new type of construction means, are more likely to cause construction site safety accidents to a certain extent owing to the lack of construction workers with matching technical training, tools, equipment, and mature safety standard systems corresponding to the process requirements. Safety concerns that may endanger workers' health and safety include musculoskeletal disorders owing to awkward body postures at offsite plants (Chu et al., 2020), risk of collision during module transportation (Ismail, 2019), risk of collision with objects, and mechanical injuries during installation (Wei et al., 2020). Hence, exploring and improving safety management studies on prefabricated construction are necessary. For instance, Jaselskis et al. (2015) suggested an innovative method for monitoring workers' behavior in the field using telepresence, Zaalouk and Han (2021) provided a parameterized workplace design optimization method for reducing workers' ergonomic injuries. Ahn et al. (2020) compared workers' safety risks between onsite and offsite construction modes during installation, and Liu et al. (2018) developed a safety risk management framework for hoisting and digital twin-based coupling model. The results of such studies have theoretical exploration significance for examining the safety management of PBs and substantial practical application value (Zhou et al., 2015).

Yet, despite the emergence of various literature reviews on safety in prefabricated construction in recent years, previous reviews focused primarily on specific aspects instead of conducting thorough and systematic analyses. For instance, Hussein and Zayed (2021) used mixed research methods to monitor and classify how to plan and operate crane prefabricated construction.

Therefore, conducting a systematic and comprehensive review is necessary to fill the research gaps. This study has five detailed objectives: 1) to develop a structured research framework for reviewing studies related to safety management in prefabricated construction; 2) to conduct science mapping to analyze primary journal publications, famous academics, and keywords in the domain of prefabrication safety management; 3) to identify the differences between prefabrication and traditional construction and summarize the characteristics of prefabrication to obtain the characteristics of prefabrication safety management; 4) to summarize the research topics; and 5) to discuss and provide signposts for potential research directions.

2. Background

2.1. Prefabrication

Prefabrication represents an innovative construction approach, involving the manufacturing of building components in specialized facilities and their on-site assembly. According to Song et al. (2022a), it is an industrialized process. Yuan et al. (2021) defines it as creating a prefabricated building using factory-made components assembled on-site. According to the volume and function of assembly unit modules, scholars from different regions have different views on and definitions for PBs, such as modular construction (Li et al., 2013), industrialized building systems (Abas et al., 2016), modular integrated construction (MiC) (Zhang et al., 2022), offsite construction (Liu et al., 2019), and so on. The concepts emphasize the typical construction process. To avoid semantic confusion, In this study, prefabrication specifically refers to a construction method where components are manufactured offsite, transported, and assembled on-site, incorporating design standardization, production industrialization, construction assembly, decoration integration, intelligent operation, and information management (Yuan et al., 2021).

2.2. Safety management

Safety is fundamentally the prevention of harm, whether to individuals, objects, or the environment (Li & Guldenmund, 2018). Safety management, as distinct from the broader concept of safety, involves specific actions and processes aimed at achieving safety objectives. These actions fall into two categories: engineering and technical measures encompassing the implementation process through equipment and technology, and behavior control involving the coordination of social relations (Fu, 2013). In this study, safety management incorporates both engineering technology and behavior control.

Safety management research traditionally revolves around two theories: risk and resilience. Risk theory, originating from Kaplan and Garrick (1981), centers on anticipating and preventing problems within a system. It emphasizes quantitative analysis and accident prevention but lacks focus on in-process and post-event stages. Resilience theory, introduced by Hollnagel and Woods (2006), shifts the paradigm by viewing system safety not merely as the absence of incidents but as a system's ability to sustain normal operations despite various circumstances or potential risks. Given the limited research on resilience perspectives, this paper primarily synthesizes literature from a risk perspective.

The application of safety management spans diverse industries, with the construction sector particularly prone to safety incidents. Construction safety management, broadly and narrowly defined, addresses the intricate challenges inherent in construction projects. In a narrow sense, it involves activities establishing safety production policies, determining necessary functions, and evaluating the safety management process. In a broader context, construction safety management encompasses planning, design, and structural safety.

Considering prefabrication as an innovative construction approach, this study delves into the novel management issues it presents compared to traditional methods. Focusing on the new construction process, the research observes and synthesizes the unique characteristics of safety management in prefabrication.

3. Methodology

This study adopted a systematic approach that involved quantitative and qualitative analyses. This approach can effectively eliminate prejudiced conclusions and subjective interpretations. Specifically, this work conducted scientometric analysis and content analysis.

The overall research framework consisting of three stages showing the review process is shown in Figure 1, and the following three subsections describe the three steps in detail.

3.1. Stage 1: literature search

To conduct the literature search, a two-step process was followed. Initially, the WoS core collection database was searched for relevant articles. One database was chosen because of the high duplication of articles and the more comprehensive coverage of WoS. However, the way of forward and backward citation will also search for articles from other databases to complement the research.

Keywords for retrieval: The keywords are divided into two categories. The first category is used to screen articles on traditional construction models. They are "prefabricate*", "modular construction", "off-site manufact*", "off-site construction", "industrialized building system", "industrial construction", "precast concrete", "panelized construction", "tilt*up construction", "modular integrated construction", "MiC", "prefabricated prefinished volumetric construction", "PPVC". The second category is used to screen articles that fall within the scope of safety management. They are "safe*", "incident*", "accident*", "risk*", "injur*", "disaster", "disease", "kill", "death".

(1) Timespan: The study was conducted using a 10-year timeframe, from 2012 to December 2022, for two reasons. First, based on the database records related to prefabrication safety, fewer than one article was published every year before 2012. Second, a 10-year observation period is a common timeframe and can provide credibility for investigating topics and trends in the research field.

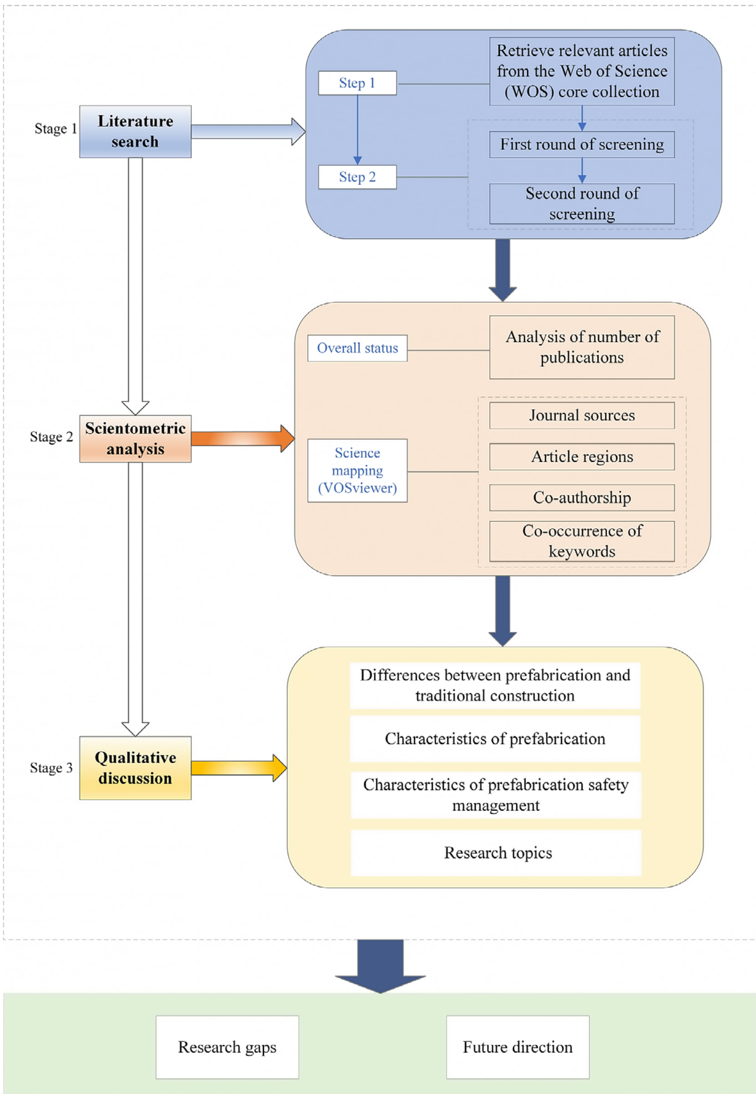

Figure 1. Research framework of review

(2) Language and type of literature: The language was limited to English, and the literature type included journal articles and conference papers.

In the first step, the initial search resulted in 2,566 documents. However, as some keywords such as "modular" are used in other fields, such as computer programming, chemistry, and biomedical material science, unrelated documents were also included. Therefore, screening was necessary in the second step.

In the second step, two rounds of screening were conducted. Initially, 144 papers were retrieved through a preliminary review process, which involved screening titles, abstracts, and keywords based on two filter criteria: 1) studies that did not fall within the scope of the construction industry and 2) titles, abstracts, and keywords that were not related to the two keyword categories above.

Next, the database search yielded 81 documents, with the following two filter criteria: 1) studies related to safety management but focused on traditional construction rather than prefabricated construction and 2) studies related to prefabrication but focused on schedule/supply chain risks rather than safety risks. Furthermore, 26 publications were added through identification by forward and backward citation chaining. The rationale behind selecting this specific research scope lies in the intention to isolate and examine safety management practices specifically within the context of prefabricated construction. By excluding studies emphasizing traditional construction safety or those primarily addressing schedule/supply chain risks in the realm of prefabrication, the aim is to delve deeply into the unique safety challenges posed by prefabricated construction methods.

The subsequent scientometric analysis was conducted on 107 articles selected after the screening process. The literature search process is illustrated in Figure 2.

3.2. Stage 2: scientometric analysis

Scientometric analysis is a quantitative method for measuring structural characteristics and tracking their development in a particular field. The analysis involves examining various factors, such as journal sources, regions, co-citation scholars, and the co-occurrence of keywords. In this study, science mapping was conducted to analyze and visually represent the scientometric networks of safety management studies. A wide range of science mapping tools have been developed for scientometric analysis (e.g., VOSviewer, CiteSpace, and BibExecl). Different bibliometric analysis tools have different capabilities and strengths. The approach was chosen, because it is well suited for visualizing large networks and used extensively in construction engineering and project management literature reviews, particularly in offsite construction (Jin et al., 2018), digital technology (Wang et al., 2020), and life cycle energy (Li et al., 2020). VOSviewer can generate various graphs based on bibliometric relationships, such as co-citation graphs for authors or journals and keyword co-occurrence graphs. In this study, VOSviewer was utilized to 1) import a data set from the WOS, 2) conduct visual analysis on the data set, and 3) analyze the correlation between the documents. This study focused on four categories in the scientific quantitative analysis, including journal sources, co-authorship, article region, and the co-occurrence of keywords. The categories are commonly used in literature review research to provide an overview of the literature sample and identify trends and patterns (Jin et al., 2018). The overall situation of the selected field can be determined in this stage, and the analysis on the co-occurring keywords can support the qualitative discussion in the next stage.

3.3. Stage 3: qualitative discussion

In stage 2, this study showed the mainstream directions of prefabrication safety research. However, conducting only clustering through a software with samples cannot effectively summarize the research topics and provide detailed information on prefabrication safety. Hence, conducting content analysis, which is a detailed and systematic examination to identify patterns, themes, or biases, is necessary. In this stage, content analysis was implemented to 1) iden-

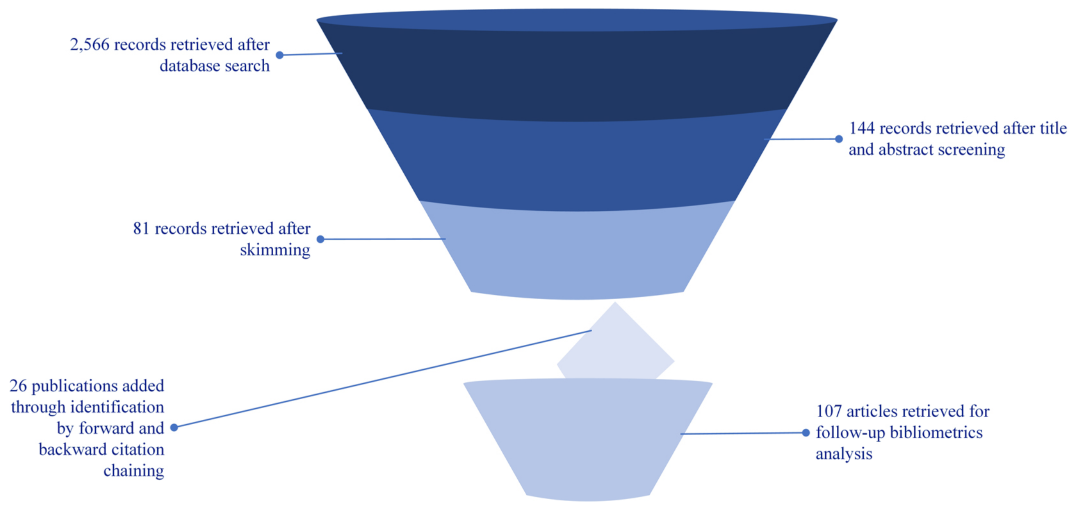

Figure 2. Screening process of literature search

tify the differences between prefabricated and traditional construction and summarize the characteristics of prefabrication to obtain the characteristics of prefabrication safety management by extracting safety activities and common accident types in different processes according to the entire prefabrication life cycle and 2) combine the findings of the keyword analysis and content analysis to summarize the research topics.

4. Scientometric information

4.1. Overview

Figure 3 displays the yearly publication trend of the journal articles in the chosen literature sample, from 2012 to December 2022.

Figure 3 shows a gradual rise in the number of publications from 2012 to December 2022. Particularly, from 2019 to 2020, a significant increase can be observed in the number of papers published. The proportion of articles published between 2019 and 2022 was the most significant in the past decade, reaching 70%. Although a sudden increase can be observed in the number of papers published in 2015, this growth was temporary. After 2019, more than 20 papers were published every year. Prefabricated safety is an emerging research field in construction engineering and management, and increased research is expected to be published.

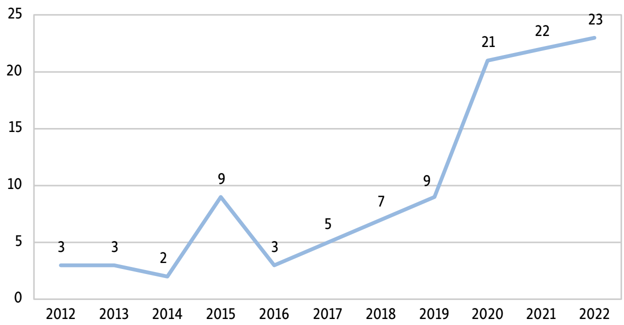

Figure 3. Number of publications (2012–2022)

4.2. Science mapping analysis

4.2.1. Journal publications

Examining the influence of a journal in a particular area of study can assist readers in acquiring the most pertinent information and promptly determining the most appropriate journal for publishing their research (Guo et al., 2017). VOSviewer was utilized in this study to identify the sources of relevant journal papers and determine the number of influential journals in the field of prefabrication safety management. Figure 4 illustrates the clustering and correlation between the articles, and Table 1 lists the journals with an average normal citation score of more than 1. This research established certain criteria to determine the number of articles and citations needed for inclusion in the analysis, with a minimum of two articles and one citation. Of the 61 identified sources, 19 met the criteria and were included in the composite network. However, some of the 19 sources lacked a connection with the other sources in the composite network, and only 15 sources formed the largest connected set. The visualization of this set of sources is shown in Figure 4.

In VOSviewer, the more the documents published in a journal, the larger the nodes. The links' thickness and distance between the nodes indicate the strength of the relationship, and different colors indicate the various clusters. In Figure 4, the node size suggested that *Automation in Construction*, *Journal of Construction Engineering and Management*, and *Engineering, Construction and Architectural Management* were likely to publish articles in the field. In addition, the publications contribute significantly to prefabrication safety management research. The journal influence quantitative measurement methods were summarized, including six major measurements. Frequency of citation is an important but controversial index. The total number of and normalized citations are strongly associ-

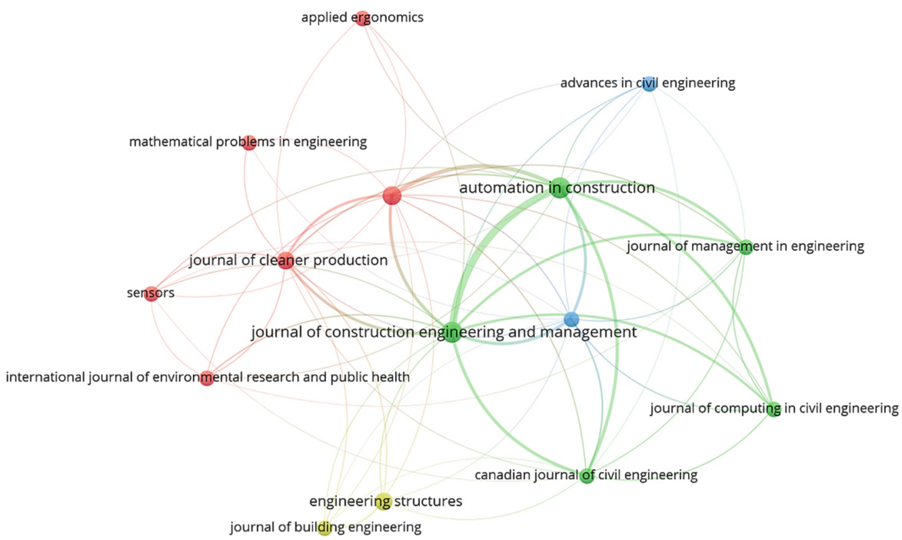

Figure 4. Visualization of main journals that published prefabrication safety management studies

ated with the number of published articles, suggesting a buildup of research output. The number of citations did not make a significant contribution to the citation analysis, and the average effect of the exclusion of the number of articles by average number of citations was observable. Average citation frequency is one of the most effective indicators to reflect the quality of a paper. The metric "average normal citations" (avg. norm. cites) can help address the misconception that old papers tend to tend to be cited considerably, simply because they have been available for a long period of time (Li et al., 2020). This research was centered on the output and influence of the articles, in which the number of articles or occurrences signified the research output. The number of articles can be directly obtained by observing the size of the nodes on the visualization graph. The average number of normal citations represented the articles' impact, which can be obtained via table sorting. Thus, this study analyzed the two indicators. It is worth noting that the two indicators were mutually independent. The same method was used in the following subsections to analyze the scholars, regions, and keywords. According to Table 1, *Applied Ergonomics*, *Journal of Computing in Civil Engineering*, *International Journal of Environmental Research and Public Health*, *Sensors*, *Journal of Cleaner Production*, and *Advanced Engineering Informatics* were the most influential journals in prefabrication safety management research. Although *Automation in Construction* had the most of articles, its average number of normal citations ranked second to the last, which suggested that the journal must enhance its influence in the domain. The metric "average publication year" (avg. pub. year) was conducive to identify the active journals in the field, such as *International Journal of Environmental Research and Public Health*, *Sensors*, and *Advanced Engineering Informatics*, which published articles in the research field in 2021 and 2022. By contrast, *Applied Ergonomics* stagnated in 2017.

4.2.2. Co-authorship

By examining the graph of the author collaboration networks, the closeness of collaboration and communication between the representative authors, teams, and academics in the research field can be determined. This research established a threshold of at least two articles and one citation for the authors, resulting in 48 of the 352 authors meeting the eligibility criteria. Figure 5 shows that the density of the nodes and strength of the links were lim-

Table 1. Quantitative analysis of journal sources of safety management studies related to prefabrication

Journal	Number of documents	Citations	Norm. citations	Avg. citations	Avg. norm. citations	Avg. pub. year
Applied Ergonomics	2	30	4.3056	15	2.1528	2017
Journal of Computing in Civil Engineering	2	34	3.6401	17	1.8201	2018
International Journal of Environmental Research and Public Health	2	3	3.3158	1.5	1.6579	2022
Sensors	2	12	3	6	1.5	2022
Journal of Cleaner Production	4	63	5.9123	15.75	1.4781	2020
Advanced Engineering Informatics	2	23	2.9302	11.5	1.4651	2021
Engineering Structures	4	128	5.3934	32	1.3484	2019
Automation in Construction	14	292	17.6671	20.8571	1.2619	2019
Journal of Building Engineering	2	19	2.3147	9.5	1.1574	2021

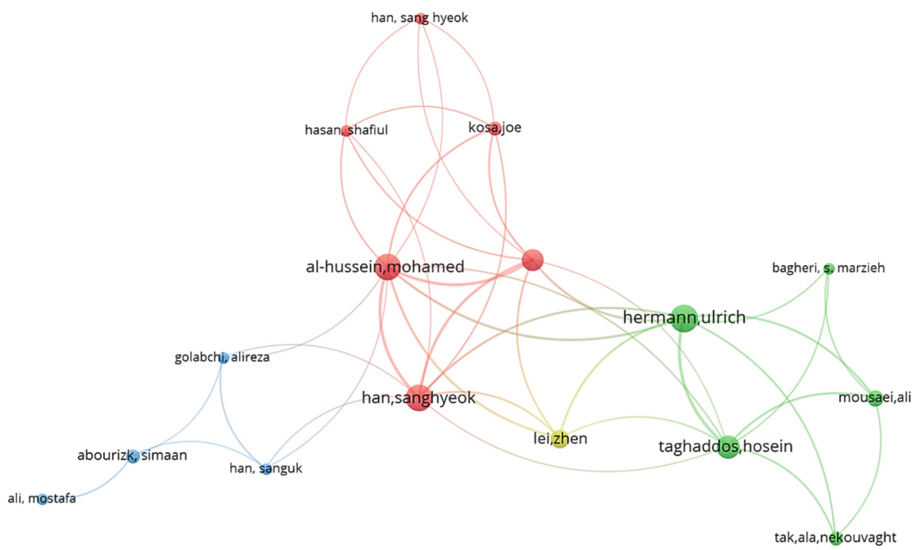

Figure 5. Analysis of co-authorship in safety management studies related to prefabrication

ited, indicating that the authors' cooperation could have been improved.

In general, three different colors represented the three main collaboration groups. For instance, Hermann, Ulrich; Taghaddos, Hosein; Tak, Ala Nekoubaght; Mousaei, Ali; and Bagheri, S. Marzieh were in the same group, which indicated that they collaborated closely with one another, transferred knowledge, and published many articles together. In addition, Hermann, Ulrich; Han, Sanghyeok; and Al-Hussein, Mohamed were the most productive scholars in the domain of prefabrication safety management in terms of the number of articles published. Table 2 shows the detailed quantitative indicators for the researchers by their average normalized citation rate. Table 2 also shows that the average number of normal citations of Hermann, Ulrich; Taghaddos, Hosein; Tak, Ala Nekoubaght; Mousaei, Ali; and Bagheri, S. Marzieh was more than 1.10, indicating that the cohort members' conclusions were unanimous. Regarding the average publication year in Table 2, Tak, Ala Nekoubaght; Mousaei, Ali; and Bagheri, S. Marzieh were the newest and most active researchers in recent years.

4.2.3. Article regions

Figure 6 and Table 3 reveal that the surveys were typically conducted within a specific country or region. In addition, countries' participation in research on prefabrication safety management was considered. Of the 16 countries, nine were selected based on the minimum requirement of VOSviewer of at least two publications and one citation. Of the nine items, one was irrelevant, and the remaining eight represented the largest relevant group on the visualization map. Figure 6 visualizes the countries active in prefabrication research. In general, increased scholarly communication between regions is necessary, and research in each country is relative. Table 3 shows that China had the highest number of publications, and the Chinese scholars had the highest number of total citations. Furthermore, South Korea had the highest average number of normalized citations, showing its current position and influence in the field. Meanwhile, Australia, China, and Iran exhibited the most recent average year of publication compared with the other countries in Table 3.

Table 2. Quantitative analysis of influential academics in the field of safety management related to prefabrication

Author	Number of documents	Citations	Norm. citations	Avg. citations	Avg. norm. citations	Avg. pub. year
Tak, Ala Nekouvaght	3	15	3.75	5	1.25	2021
Mousaei, Ali	4	19	4.75	4.75	1.1875	2021
Taghaddos, Hosein	8	141	9.1284	17.625	1.141	2019
Bagheri, S. Marzieh	2	9	2.25	4.5	1.125	2021
Hermann, Ulrich	11	185	12.2881	16.8182	1.1171	2019
Lei, Zhen	5	168	5.2726	33.6	1.0545	2016
Han, Sanghyeok	10	180	9.8761	18	0.9876	2018
Hasan, Shafiul	2	63	1.9166	31.5	0.9583	2017
Golabchi, Alireza	2	65	1.8625	32.5	0.9312	2017
Han, Sanguk	2	65	1.8625	32.5	0.9312	2017
Al-Hussein, Mohamed	10	303	9.2369	30.3	0.9237	2016
Bouferguene, Ahmed	7	136	5.9208	19.4286	0.8458	2017
Ali, Mostafa	2	12	1.4619	6	0.731	2020
Kosa, Joe	3	64	2.0384	21.3333	0.6795	2018
Abourizk, Simaan	3	26	2.0083	8.6667	0.6694	2019

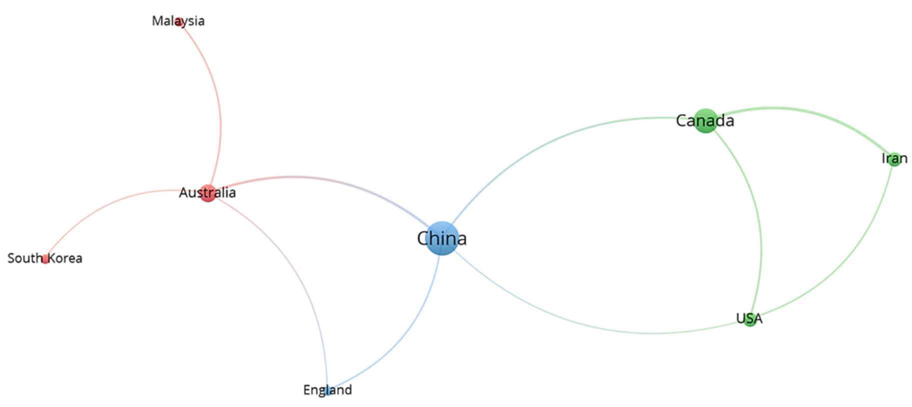

Figure 6. Analysis of regions active in safety management studies related to prefabrication

Table 3. Quantitative analysis of article region of safety management studies related to prefabrication

Country	Number of documents	Citations	Norm. citations	Avg. citations	Avg. norm. citations	Avg. pub. year
South Korea	3	62	11.0998	20.6667	3.6999	2019
England	3	74	5.3684	24.6667	1.7895	2019
Australia	11	172	15.81	15.6364	1.4373	2020
USA	7	76	9.5495	10.8571	1.3642	2018
Iran	7	85	9.061	12.1429	1.2944	2020
Canada	22	344	22.2624	15.6364	1.0119	2019
China	40	551	39.0298	13.775	0.9757	2020
Malaysia	3	7	0.6143	2.3333	0.2048	2019

4.2.4. Co-occurrence of keywords

Keywords serve as the main component of a research paper, summarizing the significant themes in a particular subject area. A network of keywords reveals knowledge about a research topic's connections, patterns, and knowledge organization. Of the 466 keywords, 448 met the initial threshold. Several criteria were used for including or excluding the keywords: 1) keywords with a minimum threshold value of 3; 2) keywords such as "OSC", "modular construction", "prefabricated construction", "building", and "construction" were excluded; and 3) keywords merging other keywords with semantic consistency, such as "3D" and "three dimensional visualization". Finally, 38 major keywords are visualized in Figure 7 and shortlisted in Table 4.

In literature text mining, the total link strength indicates the correlation or connection between a particular keyword and other keywords. This study found that "simulation", "modeling", and "construction safety" demonstrated the highest interconnectedness with the other keywords.

The average year of publication indicated the latest research on the specific keywords in prefabrication safety management. For instance, in recent years, the emerging keywords included "digital twin", "behavior", "climate", "automation", "internet", and "bim".

Based on the average number of normal citations in Table 4, the keywords with a high score were "internet", "accidents", "barriers", "China", "bim", and "design", indicating that the utilization of Internet technologies related to prefabrication was well explored. The influential studies concentrated on examining the barriers to the application of prefabrication safety management, analyzing its performance in China, and describing the processes involved in designing and using BIM technologies for enhancing safety measures in prefabricated structures.

Figure 7 illustrates that "simulation" was the most frequently mentioned research keyword, as evidenced by the size of its node. The other keywords most often associated with "simulation" were "optimization", "system", "mobile crane", "lift planning", and "algorithm", indicating that simulation methods were used to develop safety systems to monitor and control the safety of lifting equipment such as mobile cranes.

In Figure 7, the keywords were divided into four groups, displayed in four colors. The keywords in the same group tended to have close relationships with one another. For instance, "simulation", "optimization", "system", "mobile cranes", "selection", and "algorithm" were closely connected in the same cluster, which implied that they were often examined together in the same article. The links of the keywords in Figure 7 showed their relationships. For instance, "selection" and "lifting planning" were found to be closely related to "mobile cranes" and "algorithm". Nevertheless, based on the color clusters in Figure 7, it was determined that the keywords in the different clusters had a strong relationship, such as "systems" and "construction safety", or may be in the same cluster but had no relationship, such as "cost" and "projects". Based on the observations in Figure 7 and Table 4, the keyword clusters representing the most important research in the field of prefabrication safety can be identified, as follows (Jin et al., 2019):

1) Design and planning for safety involved conducting the design and planning of a project before construction from the perspective of improving safety. In Figure 7, the keyword "design" was highly linked with "models," "fatalities," and "impact" in the same cluster visualized by VOSviewer. Szymberski (1997) revealed that the design and planning phase can significantly impact the number of fatalities during construction. Models are generally developed to design a safe workplace and produce lifting plans. Therefore, by improving the planning and design phase, safety can be enhanced in the subsequent phases (Zhou et al., 2015).
2) Workers are the source and direct victims of accidents (Zhou et al., 2015). Furthermore, highly skilled construction workers are necessary to meet the demands of the widespread adoption of offsite manufacturing (OSM). A lack of professional workers could potentially lead to unsafe worker behavior and increase the likelihood of accidents (Liu et al., 2018). The keyword "worker" was highly linked with "behavior", "recognition", and "three-dimensional visualization", which were distributed in different clusters. Unsafe actions are regarded as the primary reason for the occurrence of incidents in work settings (Liu et al., 2019). Identifying dangerous actions

Table 4. Quantitative analysis of keywords in safety management studies related to prefabrication

Keyword	Total link strength	Occurrence	Avg. pub. year	Avg. citations	Avg. norm. citations
Internet	13	3	2020	13	2.062
Accidents	17	4	2018	13.5	1.7186
Barriers	9	3	2017	44.6667	1.7019
China	9	3	2017	44.6667	1.7019
BIM	23	6	2020	12.3333	1.54
Design	18	10	2019	19.7	1.4123
System	51	12	2020	15.3333	1.406
Workers	11	3	2020	8.6667	1.3923
Sites	11	3	2017	25	1.3648
Lifts	19	3	2016	28	1.3226
Selection	50	10	2019	13.8	1.3169
Fatalities	8	3	2016	20.6667	1.3091
Digital twin	16	4	2022	3.5	1.3026
Visualization	28	6	2019	14.1667	1.2938
Lift planning	27	4	2019	22.75	1.2798
Location	21	4	2019	23.25	1.2766
Construction safety	64	17	2019	17.2941	1.273
Performance	14	6	2019	13	1.2531
Safety management	43	13	2020	12.6923	1.2133
Behavior	15	5	2021	10.2	1.1824
Framework	37	9	2019	13.6667	1.1388
Three-dimensional visualization	30	6	2018	18.1667	1.1161
Mobile cranes	49	10	2019	15.5	1.1092
Opportunities	8	4	2020	8	1.1028
Algorithm	31	8	2019	17.5	1.0956
Impact	18	5	2020	12.8	1.0886
Risk management	24	6	2017	28.6667	1.0854
Recognition	8	3	2020	11	1.0209
Simulation	71	17	2019	15.4706	1.0174

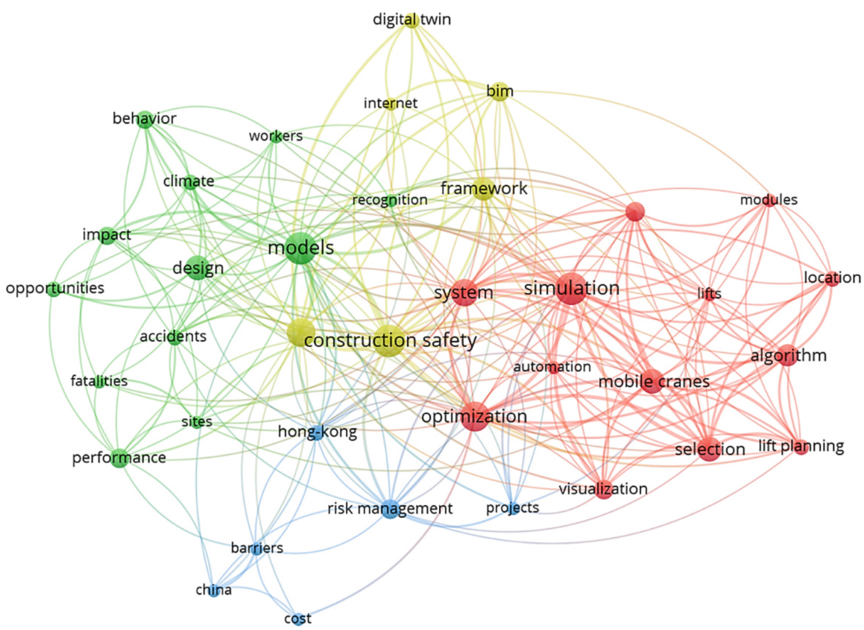

Figure 7. Mapping of keywords in safety management studies related to prefabrication

is essential for ensuring the safety of workers, and three-dimensional (3D) visualization techniques are often used to identify and monitor workers' behavior.

3) The aim of safety management and its corresponding system is to manage the conditions of people, materials, and environmental factors in the production process. Its main goal is to efficiently regulate the unsafe behaviors of individuals and unsafe conditions of materials to prevent or eliminate accidents. As things move and change, safety and risk are constantly in flux and struggle with each other. Therefore, safety management must be approached from a systemic angle. The keyword "system" had a wide connection with the other keywords in the different clusters, including "simulation", "optimization", "risk management", "performance", "cost", and so on. Safety management can generally be carried out through simulation, mainly because PBs have informatization characteristics. In addition, scientists typically develop models using specific algorithms to make predictions about the reliability and cost of safety management in prefabricated construction projects (Liu et al., 2020).
4) The utilization of information technology has become crucial in prefabrication safety management. The application of information technology involves nearly the whole process of prefabrication safety management, such as capturing images of workers' posture and using 3D technology to assess their ergonomic posture during the production of prefabricated components to reduce their awkward and improper posture (Chu et al., 2020); adopting visual technologies such as AR and VR (Joshi et al., 2021) to build a prefabrication virtual practice base to promote the quality and effectiveness of safety training, improve workers' proficiency in new construction methods, and reduce safety risks; and developing crane planning and optimization systems through integrated 4D and BIM (Tak et al., 2021).

5. Qualitative discussion

5.1. Characteristics of prefabrication safety management

5.1.1. Characteristics of construction process

Compared with the traditional method, the safety risks of prefabrication exist in not only onsite construction locations but also offsite factories. Various scholars classified the construction process. Some of the typical classifications are shown in Table 5. To effectively summarize the characteristics of the prefabrication construction process, this study classifies PBs into three links according to their whole life cycle: *pre-construction*, *during construction*, and *after construction*, and divides them into six stages, namely, *design and planning*, *manufacturing at factory plants*, *transportation from factory to site*, *onsite construction*, *maintenance/operation*, and *demolition*. The construction features can be summarized as five points.

1) High production specialization requires top-tier offsite factory conditions. Zaalouk and Han (2021) introduced a worker-friendly workplace optimization framework to enhance efficiency and reduce worker recovery-related social costs.
2) The workforce has decreased, and stringent requirements are now in place. Components for PBs are produced in a factory and then transported to the construction site for assembly, reducing the need for on-site labor and enhancing safety management, thus mitigating potential safety risks. This shift also necessitates increased specialization among workers, who must understand prefabrication methods and production lines. Li et al. (2015) employed the Proactive Construction Management System to train precast installation workers to be highly productive while prioritizing hazard awareness.
3) Mechanical equipment numbers have risen, necessitating performance enhancement. Delivery, lifting, and installation are key tasks where lifting is prominent and requires high precision. Effective and reliable transportation and lifting equipment are essential to prevent mechanical failures due to heavy workloads. Pre-lifting, device safety checks are crucial. Proper equipment selection, strengthening lifting points, and minimizing component vibrations during delivery and lifting are critical for accurate installation. To address module dimension design and transportation planning for MiC projects Zheng et al. (2023) proposed a decision-making tool. For crane operations, Han et al. (2017) introduced a 3D-based crane evaluation system (3D-CES) that can design, verify, and simulate crane operations, aiding in efficient crane selection and lift schedule planning based on safety and productivity considerations.
4) Managing prefabricated components or units is intricate. Properly arranging the stacking positions of these components before construction is essential for component safety, material quality, and the safe operation of lifting equipment. Xiao et al. (2022) shortened evacuation time by replanning the stacking position of prefabricated construction site components, equipment, and other items.
5) Prefabrication offers a cleaner work environment compared to traditional methods due to fewer onsite raw materials. Factory production and transportation of prefabricated components not only conserve resources but also notably reduce airborne dust, aligning with green development principles. Moreover, sewage and waste discharge align with green construction standards, minimizing environmental impact.

5.1.2. Safety problems in prefabrication

Through the analysis method of text mining, this study sorts the safety-related activities and common accident types in different processes during the different stages of the PB life cycle, as shown in Table 6.

1) Pre-construction: Pre-construction involves project planning and design, including structural design, detailed design (Shibin et al., 2020a, 2020b), like connection (Ma et al., 2019; Naserabad et al., 2018) and lifting node design (Minay Hashemi et al., 2020), and lifting step plan (Han et al., 2021; Lei et al., 2013; Mousaei et al., 2021). While this stage may not directly cause accidents, it greatly influences subsequent safety and should be closely monitored. Common security threats at this stage include inadequate safety considerations in design, design errors, and material structure performance issues (Li et al., 2019, 2022).

2) During construction: ThisPB process involves three stages: factory component/module manufacturing, transportation to the construction site, and on-site assembly. In the factory fabrication phase, activities with safety risks include material importation, material cutting, hoisting during component production, component splicing, and component material stacking (Jeong et al., 2022). During transportation,

Table 5. Different classifications of prefabricated construction process

Perspective	Definitions
The whole project	The stages of PB can be categorized as the decision-making stage, design stage, production and transportation stage, construction stage, and operation and maintenance stage (Weigong et al., 2020).
	Throughout the entire project life cycle, multiple complex risk factors are present across three stages: pre-construction, during construction, and after construction, which consist of the design, production, and installation phases (Song et al., 2022a).
The construction process	The complete PB construction process includes five phases: pre-construction, offsite fabrication, transportation, onsite assembly, and finishing (Yuan et al., 2021).
	The workspace, with multiple dimensions, can be categorized into three main areas: production of prefabricated components, transportation of materials and equipment, and onsite assembly (Liu et al., 2018; Abas et al., 2021; Wei et al., 2019, 2020; Yang et al., 2022).
	Prefabricated construction processes can be classified into the manufacturing process and onsite construction process (Jeong et al., 2022; Li et al., 2013).

Table 6. Safety problems in prefabrication

Link	Stage	Activities	Accident type	Safety problems	Reference
Pre-construction	Design and planning	Structural design	/	Lack of safety considerations, Error in design, Defects in structure	Han et al. (2021); Liu et al. (2022); Ma et al. (2019); MinayHashemi et al. (2020); Mousaei et al. (2021); Naserabad et al. (2018); Shibin et al. (2020a, 2020b)
		Connection design			
		Hoisting step design			
Ring construction	Manufacturing at factory plants	Material importation and loading	Falls, Collisions with falling objects, Crashes, Being caught, Cuts	Lack of management of hazard sources and unsafe behaviors, Unclear safety factors and their impact mechanism, Lack of unified safety performance evaluation system, Inadequate awareness of safety management	Ahn et al. (2020); Chu et al. (2020); Junwu and Chao (2021); Kim et al. (2012); Liu et al. (2021); Ma et al. (2020); Rubio-Romero et al. (2014); Song et al. (2022b); Tak et al. (2021); Vithanage et al. (2022); Wan et al. (2022); Xin et al. (2019); Zhang et al. (2023)
		Cutting (reinforcements, wood, and so on)			
		Component lifting			
		Unit assembly (transfer of units/modules)			
		Packing			
	Transportation from factory to site	Loading			
		Fixing Delivery			
	Onsite construction	Component/unit/module hoisting			
		Loading and stacking			
		Delivery			
		Assembly			
		Finishing			
After construction	Maintenance/operation	Monitoring	/		Yuan et al. (2021)
	Demolition	Disassembly			

lifting, placement, fixing, and transport of components or module blocks can pose safety risks (Zheng et al., 2023), with issues like lifting stability, placement accuracy, secure fixation, and transportation stability potentially leading to accidents. In on-site construction, activities include foundation work, structural, electromechanical, and decorative elements, and safety risks are associated with module hoisting, material stacking, component transportation, installation, and decoration. Safety incidents, such as falls, collisions with falling objects, crashes, entanglement, and cuts, are common during the construction phase, making it the primary stage for safety accidents in prefabrication. Security threats in this stage can result from (a) poor hazard source and unsafe behavior management, (b) unclear safety factors and their impact, (c) absence of a standardized safety performance assessment system, and (d) insufficient safety management awareness.

3) After construction: The process involves PB operation and demolition. The operation stage focuses on monitoring prefabrication's structural safety, while demolition mainly deals with disassembling PB components. However, safety performance in the demolition stage has received limited attention, resulting in few identified safety issues in this review.

5.1.3. Characteristics of prefabrication safety management

Combined with the unique features of the prefabrication process and safety concerns, it can be concluded that prefabrication safety management is complex, dynamic, and multidimensional:

1) Complexity: The multifaceted nature of PBs, with their diverse functions, introduces complexity to safety management in prefabrication. Construction environments, operating conditions, machinery, and equipment vary with different functions. Any alteration in these factors during construction can modify safety risks and introduce new hazards, impacting safety management. Furthermore, compared to traditional methods, safety management in prefabrication extends across multiple stages (factory, transportation, and site), expanding the scope and management requirements.
2) Dynamism: Managing safety in PBs is inherently dynamic (Li et al., 2022). Factors affecting prefabrication safety and their impact on the construction process change throughout the project life cycle.
3) Multidimensionality: In prefabricated construction sites, multiple parallel lifting operations can occur simultaneously, potentially causing working space overlap. Therefore, it's essential to differentiate physical space distribution, safe work space, and efficient work space based on project-specific characteristics, unlike traditional construction methods.

5.2. Summary of main research topics in prefabrication safety management

5.2.1. Publications in different project phases

This study examines the evolving stages of prefabrication safety management research by categorizing the sample documents into different phases. Figure 8 shows that articles mentioning more than one phase are counted repeatedly under each relevant phase. For instance, Lei et al. (2015) proposed a method for the design and planning phase but aimed to ensure mobile crane safety during installation. Figure 8 indicates that 94 (88%) studies focus on the construction phase, with Figure 9 further breaking down documents within this phase, highlighting researchers' substantial emphasis on on-site safety. For instance, Song et al. (2022b) concentrated on the lifting process for assembled buildings, utilized structural equation modeling to analyze lifting safety factors, and established a comprehensive safety prevention and control system. Shin (2015) explored tower crane safety at assembly sites, offering regulatory and practitioner perspectives on safe tower crane installation and dismantling. Additionally, 34 studies relate to the design and planning phase, with 25 integrating it with the construction phase. Most articles propose that safety performance can be enhanced through prevention during the design phase and efficient scheduling during planning. For example, Mousaei et al. (2021) employed an algorithm for optimizing heavy hoisting plans before operations to provide secure and efficient planning solutions. There is only one paper found on the maintenance/operation phase, which introduced a method of tilt photogrammetry using Unmanned Aerial Vehicles (UAVs) (Yao et al., 2022). However, no literature is available on the demolition phase, likely due to the relatively limited number of prefabrication projects requiring demolition compared to traditional buildings. Nevertheless, with the growing popularity of prefabrication, the need for safety management during the demolition phase is expected to increase in the future. Given the diverse construction environments involved in prefabrication, research on safety management in prefabrication should adopt a whole-life cycle approach to establish a comprehensive safety management system.

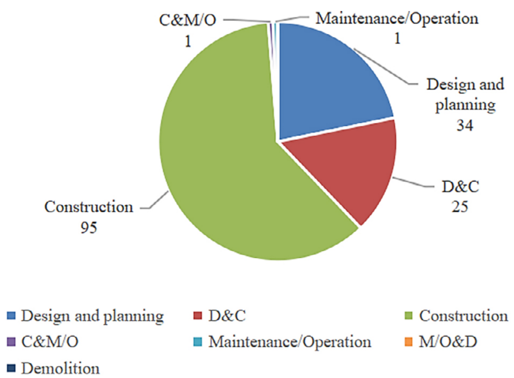

Figure 8. Publications distributed by project phase

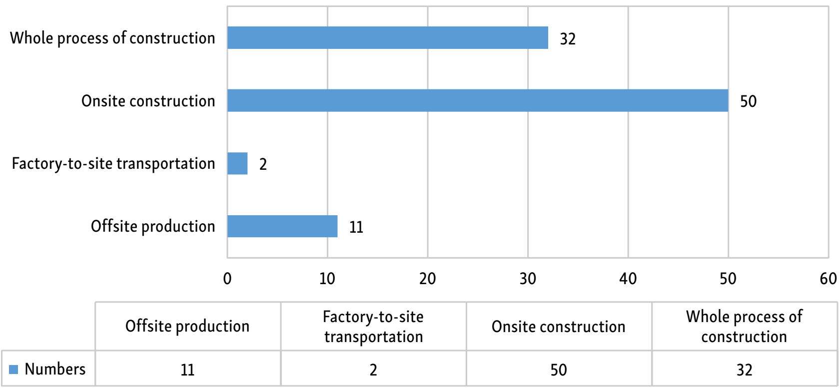

Figure 9. Publications distributed by process

5.2.2. Main research topics

The research topics related to prefabrication safety management cover a broad range but can be categorized into two main perspectives: management driven and technology driven.

5.2.2.1. Management-driven perspective

The studies from a management perspective typically addressed worker competence or behavior, the safety environment, safety assessment, safety control, and safety performance.

1) Workers' different safety attitudes and behaviors may impact their safety performance. The safety performance of workers in Off-Site Manufacturing (OSM) factories is influenced by their attitudes and behaviors. Some studies have examined worker participation, colleague support, and safety performance (Vithanage et al., 2022) or the impact of behavior attitudes and habits on safety in OSM plants (Liu et al., 2019). Safety knowledge forms the foundation, as a lack of OSM knowledge hampers safety information recognition and risk assessment. Safety education and training, including VR technology (Joshi et al., 2021), are crucial for enhancing safety knowledge and promoting positive attitudes. Additionally, researchers have addressed physical hazards, such as occupational contact allergies to amines from exposure to cement and concrete (Mowitz et al., 2016).

   However, these studies do not provide specific measures to validate results or address discrepancies in safety attitudes and behaviors among workers. Moreover, there is a notable research gap in evaluating physical hazards (e.g., lighting, temperature, space congestion, and so on) in PB factory environments.

2) Identifying safety factors is a crucial step in safety management, requiring a comprehensive and systematic approach. Researchers like Jeong et al. (2022) have gathered accident data and analyzed accidents, causes, and associated activities throughout the entire prefabrication process. Shin (2015) conducted accident analysis and engaged in focus group interviews with personnel involved in crane work. The existing methodologies for identifying safety factors in prefabrication primarily use approaches like questionnaires, expert interviews, case studies, and other research methods. These methods are guided by relevant literature, standards, and technical regulations and typically follow the 4M1E framework (Man, Machine, Material, Method, Environment).

   However, there is a noticeable research gap in comprehensively considering safety factors across the entire project construction phase. In addition, research on stakeholder engagement and safety management in prefabrication projects is currently fragmented and lacks a collaborative stakeholder management perspective when identifying safety factors. Furthermore, the criteria used for safety identification in different types of assembled buildings are relatively uniform and incomplete in terms of the factors they encompass.

   Safety assessment is a fundamental aspect of safety management, involving the quantification of identified safety factors through mathematical and rational methods. This forms the basis for a comprehensive analysis of the entire project, examining the collective impact of individual factors on the system. The outcomes of safety assessments include the identification of critical safety factors, the assessment of each factor's degree of influence, an evaluation of their interrelationships, and the establishment of the system's safety level. These assessments provide valuable insights for subsequent safety prevention and control measures. In recognition of the fuzzy and stochastic nature of safety assessment in projects, researchers, like Islam et al. (2017), have introduced methods such as fuzzy analysis networks and fuzzy Bayesian networks. To address the shortcomings in existing safety assessments, which often lack dynamic interpretation and trend prediction capabilities, Li et al. (2016) integrated system dynamics theory with Vensim software. This approach effectively analyzed risk factors in prefabricated building schedules, pinpointing key hazards for future hazard source management system development in safety management. Moreover, various studies have highlighted critical factors influencing prefabrication safety, such as worker proficiency, weather conditions, component fixation measures, and pre-delivery component quality inspection (Wei et al., 2016). Shin (2015) emphasized primary safety risks during tower crane installation or dismantling, including worker competency, stakeholder roles, the service life of crane components, and working conditions. In the context of hoisting accidents frequently occurring in prefabricated construction projects, Junwu and Chao (2021) identified a causal path starting with environmental disturbances, leading to management disorder, human error coupling, component failure, and ultimately resulting in construction safety accidents. Furthermore, Wei et al. (2020) argued that safety risk transmission during prefabrication projects falls within the workspace risk transmission category.

However, Prefabricated Buildings (PBs) are relatively new construction methods and lack a mature safety risk indicator system compared to traditional buildings. This has led to a relative shortage of research concerning the impact mechanisms and relationships between safety risk factors.

3) Safety control involves systematically selecting and developing response strategies and measures based on the identification, analysis, and evaluation of safety factors. The goal is to enhance safety management in construction enterprises, protect workers during construction, and meet safety objectives for projects. Measures should align with the project's lifecycle and prefabrication characteristics. For example, Xin et al. (2019) proposed comprehensive measures for construction sites, design and construction coordination, and industry development. These encompass site acceptance, support systems, scaffolding, and safety protection during construction. In design and coordination, the authors recommended the Engineering, Procurement, and Construction (EPC) mode and comprehensive safety standards, covering responsibilities, management processes, and technical specifications for PB construction.

However, there is limited research on integrating technology and management methods into systematic frameworks, and the effectiveness of control measures remains underexplored, lacking qualitative or quantitative assessments.

4) Safety performance is closely tied to project cost, driving the exploration of multi-objective optimization. For example, Wei et al. (2019) employed system dynamics to analyze safety incidents in prefabrication and recommended improving component hoisting technology, enhancing delivery inspections, upgrading safety identification technology, and optimizing specialized transport vehicle use to balance safety, progress, and cost.

Understanding internal safety factors like equipment, workers, and the construction environment, as well as external influences, is vital. Given the high cost of prefabrication, companies may weigh accident risks against financial gains. Government oversight of safety regulation in the prefabrication industry is essential to prevent cost-saving measures that compromise safety.

5.2.2.2. Technology-driven perspective

Prefabrication heavily relies on technology to leverage its unique features. Tools like digital twins, 3D, 4D, VR, AR, and BIM are prevalent in prefabrication, enhancing visualization and efficiency. Digital twin tech and AI algorithms optimize safe lifting paths, site layouts, and workplace designs. Additionally, 3D and 4D visualization simulate worker postures, lifting equipment, and environments, offering visual safety benefits to designers. These technology applications encompass safety planning and design, training, and monitoring.

1) Ergonomic workplace design is crucial in factories with repetitive production tasks. Musculoskeletal disorders are a common cause of nonfatal occupational injuries, leading to extended absences and potential disability. To address these risks, Chu et al. (2020) used a motion data-driven analysis framework, incorporating 3D visualization and ergonomics to optimize workplace layouts. Li et al. (2019) developed a visual system with 3D technology for automated ergonomic risk assessment, reducing assessment time and errors. Case studies validated the feasibility of these design frameworks.

Improving prefabrication safety during transportation and hoisting involves planning and design in the pre-construction phase. Researchers have developed optimization algorithms for various aspects. For instance, Zheng et al. (2023) recommended a hybrid truck with satellite guidance for safe transportation, using cost functions and parallel calculations for different-sized vehicles. To enhance construction efficiency, simultaneous crane use is common, and a new path planner for double-crane lifting was designed to prevent collisions and improve flexibility (Cai et al., 2018). Additionally, (Han et al., 2017) created a 3D-based crane evaluation system (3D-CES) for digital crane information to aid in crane selection and design.

2) In prefabrication safety management, technology-driven safety training can help overcome the shortage of skilled workers and the disruption caused by on-site training. It creates virtual construction environments and simulations. For instance, Jaselskis et al. (2015) used real-time positioning and 3D technology to track workers and resources and recommended incorporating real-time feedback and post-event analysis into training without interfering with on-site work. While current safety training typically uses visual technology with simple scenarios, future research can explore interactive technologies and practical project integration.

3) PB safety monitoring primarily focuses on modular construction environments and equipment motion. For example, Pooladvand et al. (2021) used VR technology to create a crane simulation system for real-time quantitative safety monitoring of lifting paths. Han et al. (2016) employed 3D technology and an algorithm to monitor crane movement and potential collision risks.

In addition, Zhong and Qin (2022) used BIM and laser scanning to achieve precise positioning of assembled building components during the assembly process.

Safety monitoring primarily emphasizes equipment safety and environmental monitoring, yet there's a need for research on human behavior and motion. Additionally, systematic monitoring of people, the environment, and equipment is essential.

This study lacks literature on emerging technology applications in early warning systems for security. This gap is due to the relatively recent development of research in the safety monitoring stage. Early safety warnings should rely on reliable monitoring of equipment, people, and the environment to identify danger zones and issue warnings.

6. Research trends in prefabrication safety management

Building on the previous examination of the keywords, research topics, and current status of prefabrication safety management research, Figure 10 summarizes the main research hotspots and their current status in the domain of prefabrication safety management and proposes some future academic directions.

1) Take external conditions into factor analysis. Compared with conventional construction, prefabrication increases the process of plant construction and road transportation, thereby increasing the risk space. Therefore, conducting relevant studies on the two phases is necessary, such as increasing research on the impact of safety factors on the external environment of a plant (e.g., noise, temperature, humidity, etc.) instead of focusing only on the lifting process during the construction phase. For example, Dong et al. (2024) provided personalized exposure risk assessment and corresponding mitigation management measures for workers exposed to risks by using the Damage Assessment and Cyclic Mitigation (DACM) model. Construction safety is closely related to workers' behavior and awareness. In examining the safety of PBs, a comparison with traditional construction is suggested, focusing on the impact of the similarities and differences between the two construction methods on safety performance as well as discussing how to transform the traditional workers into the highly efficient and skilled workers. Continuously exploring the issue of aging workers and functions of returning workers in the future would be worthwhile, as an increasing number of young people are turning away from a career in construction.

2) Identifying safety factors of prefabrication needs to be more comprehensive. Different stakeholders are the main bodies driving the development of a field. High-rise prefabricated assembled buildings are gradually emerging, but currently, studies on safety management for different project types are few. In the future, research on stakeholders, and case studies on high-rise prefabricated assembled buildings are expected to increase.

Integrate the systematic framework of safety identification and assessment. Compared with the traditional model, prefabrication safety management emerged only recently, and prefabrication standards and evaluation criteria have yet to reach a consistent level. Research on the safety management of different stakeholders is also limited. However, different stakeholders are the main bodies driving the development of a field, so integrating the systematic framework of different stakeholders is necessary. In the existing research, most studies consider safety factors static and independent of each other and customarily use static research methods, such as hierarchical analysis, gray cluster analysis, etc., lacking research on crucial safety factors, the relationship between safety factors, and the influence path. Therefore, the future research methods need to study the risk measurement and simulation of prefabrication safety in depth from the perspective of dynamic and complex system theory. Also, safety assessments should be analyzed in conjunction with project performance.

3) Build a systematic safety management framework and propose methods that can measure the effectiveness of safety measures. Safety control should combine technology and management methods to form holistic measures, which will help improve the safety prevention and emergency response capability of equipment and environment and improve the safety attitude and awareness of enterprises and workers. The effectiveness of safety management measures helps to promote the project's safety, and how to evaluate the effectiveness of measures is also a trend of future research. In addition, resilience, as a new concept in safety management, can also be applied to the safety management framework of prefabricated buildings, offering a fresh perspective for research (Wang et al., 2024).

4) Multi-objective research on safety performance should be strengthened. Risk studies on PBs involve productivity, cost, quality, and safety, and one risk is often related to other risks. For instance, one potential avenue of research on prefabrication safety management could be exploring the correlation between lean technology and safety performance.

5) Different technologies should be integrated, and the practicality of the technology should be considered. For the technical application of prefabricated safety management, suitable methods or models should be applied to research based on different types of PBs and technical requirements at various stages. At the same time, the advantages of such methods can be complemented by research on methods and technologies from different fields, such as assembly line production in manufacturing, combined with posture evaluation in ergonomics. Integration with other emerging information technologies, such as DT, UVB, VR, AI, and so on, should be strengthened to improve the practicality and operability of technology applications, conduct research in conjunction with safety issues in actual engineering, and improve the transformation of technology applications, from laboratory research to field construction.

7. Conclusions

This study adopted a systematic three-stage approach of bibliometric search, scientometric analysis, and qualitative discussion to review articles published on prefabrication safety management from 2012 to December 2022. Through two rounds of literature screening, 107 articles

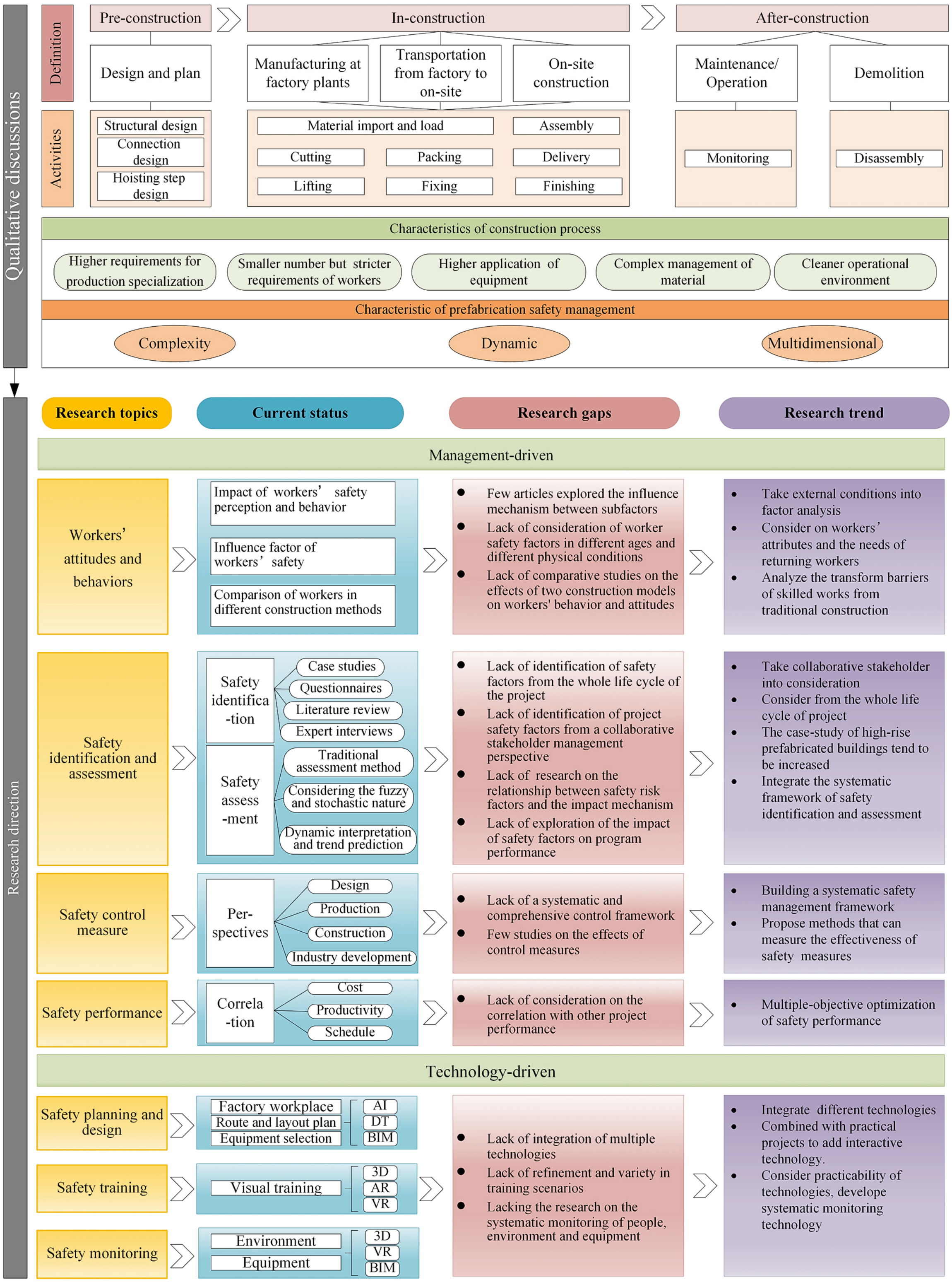

Figure 10. Summary framework of current status of prefabrication safety for future directions

were selected as the final sample to identify the research trends in recent years. The findings of the scientometric analysis are presented below.

1) The journals that publish articles in the domain of prefabrication safety management included *Applied Ergonomics*, *Journal of Computing in Civil Engineering*, *International Journal of Environmental Research and Public Health*, *Sensors*, *Journal of Cleaner Production*, and *Advanced Engineering Informatics*, which were identified as the most impactful journals.
2) Cooperation among authors could be improved. Tak, Ala Nekoubaght; Mousaei, Ali; and Bagheri, S. Marzieh were the most active academics recently, whereas Hermann, Ulrich; Han, Sanghyeok; and Al-Hussein, Mohamed were the most prolific researchers in the domain of prefabrication safety management.
3) Academic exchanges between regions should be increased, and research is relative across countries. South Korea demonstrated the highest average number of normalized citations, implying its prominent role in the field. Meanwhile, Australia, China, and Iran were the most active countries recently.
4) In this study, "simulation", "modeling", and "construction safety" were the keywords most interrelated with the other keywords. According to the reclassification of the keywords, the research directions of prefabrication safety management can be categorized as safety design and planning, workers' problems, safety management and support systems, and the application of information technology.

Further qualitative analysis was conducted to obtain the characteristics of prefabricated construction safety management compared with traditional construction, as follows:

1) High requirements for production specialization;
2) Decreased number of workers but extremely strict requirements;
3) Increased number of mechanical equipment and improvement requirements for performance;
4) Highly complex management for prefabricated components or units;
5) Clean operation environment owing to few raw materials onsite.

Meanwhile, this review summarized the research topics in precast safety management into two research perspectives, that is, a management-driven perspective and technology-driven perspective; discussed the current status; and proposed future research directions, including:

1) Considering workers' attributes and the needs of returning workers and analyzing the transformation barriers of skilled work from traditional construction;
2) Identifying safety factors of prefabrication needs to be more comprehensive and integrating the systematic framework of safety identification and assessment;
3) Proposing methods that can measure the effectiveness of safety measures;
4) Strengthening multi-objective research and examining prefabrication from a whole-life-cycle perspective;
5) Integrating different technologies and considering their practicality (e.g., IoT, 3D, 4D, and digital twins).

This review offers significant contributions to the field of prefabricated building safety management, as follows:

1) Provides a systematic and comprehensive research framework. The review presents a well-structured framework for safety management research in prefabricated buildings, serving as a valuable guide for novice researchers.
2) Explores research hotspots from both management and technological perspectives. By addressing safety management research from multiple angles – both managerial and technological – the review enables experienced researchers to swiftly identify emerging trends and gaps in the field.

Overall, the review not only aids in the rapid identification of influential journals and articles but also significantly advances the research landscape in prefabricated safety management. It fosters a deeper understanding of the field and inspires new research directions. However, as the field is still evolving and the available literature is limited, future research should focus on expanding the database and incorporating case studies to enrich the body of knowledge.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (NSFC) (Grant No. 52078302), the National Natural Science Foundation of Guangdong Province (Grant No. 2021A1515012204), the Department of Education of Guangdong Province (Grant No. 2021ZDZX1004), the Shenzhen Science and Technology Innovation Commission (Grant No. JCYJ20190808174409266, GJHZ20200731095806017, SGDX20201103093600002, and JCYJ20220818102211024).

References

Abas, N. H., Blismas, N., & Lingard, H. (2016). Knowledge-based energy damage model for evaluating industrialised building systems (IBS) occupational health and safety (OHS) risk. In N. A. Rahman, Z. M. Jaini, R. Yunus, & S. N. Rahmat (Eds.), *3rd International Conference on Civil and Environmental Engineering for Sustainability* (*ICONCEES 2015*) (Vol. 47, Article 04015). EDP Sciences. https://doi.org/10.1051/matecconf/20164704015

Abas, N. H., Blismas, N., & Lingard, H. (2021). Development of risk assessment tool using damaging energy and argumentation theory for evaluating construction occupational safety and health risks. *Engineering, Construction and Architectural Management*, *28*(10), 2967–2993. https://doi.org/10.1108/ECAM-07-2020-0486

Ahn, S., Crouch, L., Kim, T. W., & Rameezdeen, R. (2020). Comparison of worker safety risks between onsite and offsite construction methods: A site management perspective. *Journal of Construction Engineering and Management*, *146*(9), Article 05020010. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001890

Cai, P., Chandrasekaran, I., Zheng, J., & Cai, Y. (2018). Automatic path planning for dual-crane lifting in complex environments using a prioritized multiobjective PGA. *IEEE Transactions on Industrial Informatics*, *14*(3), 829–845. https://doi.org/10.1109/TII.2017.2715835

Chu, W., Han, S., Luo, X., & Zhu, Z. (2020). Monocular vision-based framework for biomechanical analysis or ergonomic posture assessment in modular construction. *Journal of Computing in Civil Engineering*, *34*(4), Article 04020018. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000897

Dong, Z., Qin, R., Zou, P., Yao, X., Cui, P., Zhang, F., & Yang, Y. (2024). Occupational health risk assessment of PC production-caused pollution based on damage assessment and cyclic mitigation model. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-06-2023-0581

Fu, G. (2013). *Safety management*. *A behavior-based approach to accident prevention*. Science Press.

Guo, H., Yu, Y., & Skitmore, M. (2017). Visualization technology-based construction safety management: A review. *Automation in Construction*, *73*, 135–144. https://doi.org/10.1016/j.autcon.2016.10.004

Han, S., Lei, Z., Bouferguene, A., Al-Hussein, M., & Hermann, U. (2016). 3D visualization-based motion planning of mobile crane operations in heavy industrial projects. *Journal of Computing in Civil Engineering*, *30*(1), Article 04014127. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000467

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

Han, S., Lei, Z., Hermann, U., Bouferguene, A., & Al-Hussein, M. (2021). 4D-based automation of heavy lift planning in industrial construction projects. *Canadian Journal of Civil Engineering*, *48*(9), 1115–1129. https://doi.org/10.1139/cjce-2019-0825

Hollnagel, E., & Woods, D. (2006). *Epilogue*: *Resilience engineering-concepts and precepts*. Aldershot: Ashgate Publishing.

Hong Kong Labour Department. (2020). https://www.labour.gov.hk/eng/osh/content10.htm

Hussein, M., & Zayed, T. (2021). Crane operations and planning in modular integrated construction: Mixed review of literature. *Automation in Construction*, *122*, Article 103466. https://doi.org/10.1016/j.autcon.2020.103466

Islam, M. S., Nepal, M. P., Skitmore, M., & Attarzadeh, M. (2017). Current research trends and application areas of fuzzy and hybrid methods to the risk assessment of construction projects. *Advanced Engineering Informatics*, *33*, 112–131. https://doi.org/10.1016/j.aei.2017.06.001

Ismail, Z.-A. (2019). Optimising the safety of road transport workers on IBS building construction projects: A review. *Social Responsibility Journal*, *15*(6), 837–851. https://doi.org/10.1108/SRJ-09-2018-0240

Jaselskis, E., Sankar, A., Yousif, A., Clark, B., & Chinta, V. (2015). Using telepresence for real-time monitoring of construction operations. *Journal of Management in Engineering*, *31*(1), Article A4014011. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000336

Jeong, G., Kim, H., Lee, H.-S., Park, M., & Hyun, H. (2022). Analysis of safety risk factors of modular construction to identify accident trends. *Journal of Asian Architecture and Building Engineering*, *21*(3), 1040–1052. https://doi.org/10.1080/13467581.2021.1877141

Jin, R., Gao, S., Cheshmehzangi, A., & Aboagye-Nimo, E. (2018). A holistic review of off-site construction literature published between 2008 and 2018. *Journal of Cleaner Production*, *202*, 1202–1219. https://doi.org/10.1016/j.jclepro.2018.08.195

Jin, R., Zou, P. X. W., Piroozfar, P., Wood, H., Yang, Y., Yan, L., & Han, Y. (2019). A science mapping approach based review of construction safety research. *Safety Science*, *113*, 285–297. https://doi.org/10.1016/j.ssci.2018.12.006

Joshi, S., Hamilton, M., Warren, R., Faucett, D., Tian, W., Wang, Y., & Ma, J. (2021). Implementing virtual reality technology for safety training in the precast/prestressed concrete industry. *Applied Ergonomics*, *90*, Article 103286. https://doi.org/10.1016/j.apergo.2020.103286

Junwu, W., & Chao, L. (2021). On the cause-result consequence of the hoisting accidents in the prefabricated construction projects from the perspective of relevance. *Journal of Safety and Environment*, *21*(3), 1158–1164.

Kaplan, S., & Garrick, B. J. (1981). On the quantitative definition of risk. *Risk Analysis*, *1*(1), 11–27. https://doi.org/10.1111/j.1539-6924.1981.tb01350.x

Kim, S., Nussbaum, M. A., & Jia, B. (2012). The benefits of an additional worker are task-dependent: Assessing low-back injury risks during prefabricated (panelized) wall construction. *Applied Ergonomics*, *43*(5), 843–849. https://doi.org/10.1016/j.apergo.2011.12.005

Lei, Z., Taghaddos, H., Hermann, U., & Al-Hussein, M. (2013). A methodology for mobile crane lift path checking in heavy industrial projects. *Automation in Construction*, *31*, 41–53. https://doi.org/10.1016/j.autcon.2012.11.042

Lei, Z., Han, S., Bouferguene, A., Taghaddos, H., Hermann, U., & Al-Hussein, M. (2015). Algorithm for mobile crane walking path planning in congested industrial plants. *Journal of Construction Engineering and Management*, *141*(2), Article 05014016. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000929

Li, Y., & Guldenmund, F. W. (2018). Safety management systems: A broad overview of the literature. *Safety Science*, *103*, 94–123. https://doi.org/10.1016/j.ssci.2017.11.016

Li, H. X., Al-Hussein, M., Lei, Z., & Ajweh, Z. (2013). Risk identification and assessment of modular construction utilizing fuzzy analytic hierarchy process (AHP) and simulation. *Canadian Journal of Civil Engineering*, *40*(12), 1184–1195. https://doi.org/10.1139/cjce-2013-0013

Li, H., Lu, M., Chan, G., & Skitmore, M. (2015). Proactive training system for safe and efficient precast installation. *Automation in Construction*, *49*, 163–174. https://doi.org/10.1016/j.autcon.2014.10.010

Li, C. Z., Hong, J., Xue, F., Shen, G. Q., Xu, X., & Mok, M. K. (2016). Schedule risks in prefabrication housing production in Hong Kong: A social network analysis. *Journal of Cleaner Production*, *134*, 482–494. https://doi.org/10.1016/j.jclepro.2016.02.123

Li, C. Z., Lai, X., Xiao, B., Tam, V. W. Y., Guo, S., & Zhao, Y. (2020). A holistic review on life cycle energy of buildings: An analysis from 2009 to 2019. *Renewable and Sustainable Energy Reviews*, *134*, Article 110372. https://doi.org/10.1016/j.rser.2020.110372

Li, X., Han, S., Gul, M., & Al-Hussien, M. (2019). Automated post-3D visualization ergonomic analysis system for rapid workplace design in modular construction. *Automation in Construction*, *98*, 160–174. https://doi.org/10.1016/j.autcon.2018.11.012

Li, Z., Zhang, S., Meng, Q., & Hu, X. (2021). Barriers to the development of prefabricated buildings in China: A news coverage analysis. *Engineering, Construction and Architectural Management*, *28*(10), 2884–2903. https://doi.org/10.1108/ECAM-03-2020-0195

Li, X., Wang, C., Kassem, M. A., Alhajlah, H. H., & Bimenyimana, S. (2022). Evaluation method for quality risks of safety in prefabricated building construction using SEM-SDM approach. *International Journal of Environmental Research and Public Health*, *19*(9), Article 5180. https://doi.org/10.3390/ijerph19095180

Liu, J., Gong, E., Wang, D., & Teng, Y. (2018). Cloud model-based safety performance evaluation of prefabricated building project in China. *Wireless Personal Communications*, *102*(4), 3021–3039. https://doi.org/10.1007/s11277-018-5323-3

Liu, Q., Ye, G., & Feng, Y. (2019). Workers' safety behaviors in the off-site manufacturing plant. *Engineering, Construction and Architectural Management*, *27*(3), 765–784. https://doi.org/10.1108/ECAM-03-2019-0136

Liu, H., He, Y., Hu, Q., Guo, J., & Luo, L. (2020). Risk management system and intelligent decision-making for prefabricated building project under deep learning modified teaching-learning-based optimization. *PLoS ONE*, *15*(7), Article e0235980. https://doi.org/10.1371/journal.pone.0235980

Liu, Z., Meng, X., Xing, Z., & Jiang, A. (2021). Digital twin-based safety risk coupling of prefabricated building hoisting. *Sensors*, *21*(11), Article 3583. https://doi.org/10.3390/s21113583

Liu, Z.-S., Meng, X.-T., Xing, Z.-Z., Cao, C.-F., Jiao, Y.-Y., & Li, A.-X. (2022). Digital twin-based Intelligent safety risks prediction of prefabricated construction hoisting. *Sustainability*, *14*(9), Article 5179. https://doi.org/10.3390/su14095179

Ma, W., Li, Y., Ding, K., Cheng, B., Liu, J., Hao, J., & Tam, V. W. Y. (2019). Mechanical properties of new dry-type beam-column Bolt connection joint. *Sustainability*, *11*(12), Article 3348. https://doi.org/10.3390/su11123348

Ma, H., Zhang, H., & Chang, P. (2020). 4D-based workspace conflict detection in prefabricated building constructions. *Journal of Construction Engineering and Management*, *146*(9), Article 04020112. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001883

MinayHashemi, S., Han, S., Olearczyk, J., Bouferguene, A., Al-Hussein, M., & Kosa, J. (2020). Automated rigging design for heavy industrial lifts. *Automation in Construction*, *112*, Article 103083. https://doi.org/10.1016/j.autcon.2020.103083

Ministry of Housing and Urban-Rural Development. (2019). *Circular of the General Office of the Ministry of Housing and Urban-Rural Development on the production safety accidents of municipal housing engineering*.

Mousaei, A., Taghaddos, H., Bagheri, S. M., & Hermann, U. (2021). Optimizing heavy lift plans for industrial construction sites using Dijkstra's algorithm. *Journal of Construction Engineering and Management*, *147*(11), Article 04021160. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002157

Mowitz, M., Zimerson, E., Hauksson, I., & Ponten, A. (2016). Chromate and amine contact allergies in workers manufacturing precast concrete elements. *Contact Dermatitis*, *75*(6), 363–369. https://doi.org/10.1111/cod.12661

Naserabad, A. A., Ghasemi, M. R., Shabakhty, N., & Arab, H. G. (2018). Evaluation of three support shapes on behavior of new bolted connection BBCC in modularized prefabricated steel structures. *International Journal of Steel Structures*, *18*(5), 1639–1653. https://doi.org/10.1007/s13296-018-0051-9

Pooladvand, S., Taghaddos, H., Eslami, A., Tak, A. N., & Hermann, U. (2021). Evaluating mobile crane lift operations using an interactive virtual reality system. *Journal of Construction Engineering and Management*, *147*(11), Article 04021154. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002177

Rubio-Romero, J. C., Suarez-Cebador, M., & Abad, J. (2014). Modeling injury rates as a function of industrialized versus on-site construction techniques. *Accident Analysis and Prevention*, *66*, 8–14. https://doi.org/10.1016/j.aap.2014.01.005

Shibin, D., Mingjiao, X., Qiong, B., Yu, L., Jing, W., Wenyi, K., Bo, D., & Bo, L. (2020a). Design of assembly structure in Chengdu Construction Engineering Pre-built Technology R&D Center. *Building Structure*, *50*(19), 117–123.

Shibin, D., Qiong, B., Jing, W., Mingjiao, X., Yu, L., & Huan, W. (2020b). Assembly structural design of Emerging Industrial Park Service Center. *Building Structure*, *50*(20), 97–102.

Shin, I. J. (2015). Factors that affect safety of tower crane installation/dismantling in construction industry. *Safety Science*, *72*, 379–390. https://doi.org/10.1016/j.ssci.2014.10.010

Song, L., Li, H., Deng, Y., & Li, C. (2022a). Understanding safety performance of prefabricated construction based on complex network theory. *Applied Science*, *12*(9), Article 4308. https://doi.org/10.3390/app12094308

Song, Y., Wang, J., Liu, D., & Guo, F. (2022b). Study of occupational safety risks in prefabricated building hoisting construction based on HFACS-PH and SEM. *International Journal of Environmental Research and Public Health*, *19*(3), Article 1550. https://doi.org/10.3390/ijerph19031550

Szymberski, R. T. (1997). Construction project safety planning. *Tappi Journal*, *80*(11), 69–74.

Tak, A. N., Taghaddos, H., Mousaei, A., Bolourani, A., & Hermann, U. (2021). BIM-based 4D mobile crane simulation and onsite operation management. *Automation in Construction*, *128*, Article 103766. https://doi.org/10.1016/j.autcon.2021.103766

Vithanage, S. C., Sing, M. C. P., Davis, P., & Newaz, M. T. (2022). Assessing the off-site manufacturing workers' influence on safety performance: A Bayesian network approach. *Journal of Construction Engineering and Management*, *148*(1), Article 04021185. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002224

Wan, P., Wang, J., Liu, Y., Lu, Q., & Yuan, C. (2022). On Risk probability of prefabricated building hoisting construction based on multiple correlations. *Sustainability*, *14*(8), Article 4430. https://doi.org/10.3390/su14084430

Wang, M., Wang, C. C., Sepasgozar, S., & Zlatanova, S. (2020). A systematic review of digital technology adoption in off-site construction: Current status and future direction towards Industry 4.0. *Buildings*, *10*(11), Article 204. https://doi.org/10.3390/buildings10110204

Wang, J., Chen, Z., Song, Y., Liu, Y., He, J., & Ma, S. (2024). Data-driven dynamic Bayesian network model for safety resilience evaluation of prefabricated building construction. *Buildings*, *14*(3), Article 570. https://doi.org/10.3390/buildings14030570

Wei, C., Jie, F., Fugang, X., & Jie, Y. (2016). Grey clustering evaluation model for construction safety of fabricated building project. *China Safety Science Journal*, *26*(11), 70–75.

Wei, C., Zhi, Q., Fugang, X., Li, N., & Daohe, Y. (2019). SD-MOP model for preventing prefabricated construction safety accidents. *China Safety Science Journal*, *29*(1), 19–24.

Wei, C., Zhuzhang, Y., Wei, X., Fugang, X., Daohe, Y., & Li, N. (2020). Research on DEMATEL-BN model of construction risk transmission for prefabricated building. *China Safety Science Journal*, *30*(7), 1–6.

Weigong, C., Huiying, Y., & Zhiguo, G. (2020). On maintenance life cycle safety assessment of prefabricated buildings in regard to its vulnerability. *Journal of Safety and Environment*, *20*(6), 2069–2078.

Xiao, M., Zhou, X., Pan, X., Wang, Y., Wang, J., Li, X., Sun, Y., & Wang, Y. (2022). Simulation of emergency evacuation from construction site of prefabricated buildings. *Scientific Reports*, *12*(1), Article 2732. https://doi.org/10.1038/s41598-022-06211-w

Xin, G., Linyan, C., Zongjie, P., & Zhou, L. (2019). Construction risk control Mechanism for fabricated concrete structure. *Journal of Tongji University*. *Natural Science*, *47*(11), 1676–1682.

Yang, B., Zhang, B., Zhang, Q., Wang, Z., Dong, M., & Fang, T. (2022). Automatic detection of falling hazard from surveillance videos based on computer vision and building information modeling. *Structure and Infrastructure Engineering*, *18*(7), 1049–1063. https://doi.org/10.1080/15732479.2022.2039217

Yao, J., Na, J., Ma, R., & Wang, Y. (2022). The key technology of oblique photogrammetry of assembled buildings by UAV. *Advances in Multimedia*, *2022*, Article 6267403. https://doi.org/10.1155/2022/6267403

Yuan, Y., Ye, S., & Lin, L. (2021). Process monitoring with support of IoT in prefabricated building construction. *Sensors and Materials*, *33*(4), 1167–1185. https://doi.org/10.18494/SAM.2021.3003

Zaalouk, A., & Han, S. (2021). Parameterized design optimization framework for worker-friendly workplaces in modular construction. *Journal of Construction Engineering and Management*, *147*(5), Article 04021030. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002029

Zhang, Z., Pan, W., & Pan, M. (2022). Critical considerations on tower crane layout planning for high-rise modular integrated construction. *Engineering*, *Construction and Architectural Management*, *29*(7), 2615–2634. https://doi.org/10.1108/ECAM-03-2021-0192

Zhang, Y., Yi, X., Li, S., & Qiu, H. (2023). Evolutionary game of government safety supervision for prefabricated building construction using system dynamics. *Engineering*, *Construction and Architectural Management*, *30*(7), 2947–2968. https://doi.org/10.1108/ECAM-06-2021-0501

Zheng, Z., Pan, M., Yang, Y., & Pan, W. (2023). Motion planning for efficient and safe module transportation in modular integrated construction. *Computer-Aided Civil and Infrastructure Engineering*, *38*(5), 580–600. https://doi.org/10.1111/mice.12835

Zhong, Y., & Qin, Z. (2022). Positioning of prefabricated building components based on BIM and laser image scanning technology in the environment of Internet of Things. *Computational Intelligence and Neuroscience*, *2022*, Article 5976935. https://doi.org/10.1155/2022/5976935

Zhou, Z., Goh, Y. M., & Li, Q. (2015). Overview and analysis of safety management studies in the construction industry. *Safety Science*, *72*, 337–350. https://doi.org/10.1016/j.ssci.2014.10.006