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Visual Analysis of Research Hotspots and Future Directions in Construction Safety for Prefabricated Buildings

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Abstract: Through the application of bibliometric and social network analysis (SNA) techniques, this study examines the scholarly literature on the intersection of "prefabricated buildings" and "construction safety", utilizing data from CNKI and Web of Science. By employing CiteSpace, a comprehensive analysis was conducted to identify key themes, explore temporal dynamics, and visualize the current state of research, as well as its hotspots and future trends. The results reveal limited collaboration and knowledge exchange among Chinses researchers, with research emphasis primarily centered on influencing factors, construction techniques, and intelligent construction methods. Presently, China is in the developmental phase of prefabricated building research, as evidenced by the increasing volume of studies in this domain. Nevertheless, research on the safety of prefabricated building construction exhibits a highly uneven distribution, necessitating a more refined focus in research directions. The outcomes of this study will offer valuable insights and references for analyzing the frontier and trends in prefabricated building construction safety research

Keywords: Prefabricated Buildings; CiteSpace; Construction Safety; Knowledge Mapping; Visualization

1. Introduction

As China's demographic dividend wanes and construction technology advances, a pressing need for energy conservation and emission reduction has propelled prefabricated building construction into a new era[1]. Facing a substantial market scale, the swift and effective promotion of prefabricated construction, while ensuring construction safety and reducing hazards in the construction process, stands as pivotal endeavors to prevent safety accidents, potential casualties, and mitigate economic losses, ensuring a secure construction environment and the steady advancement of prefabricated buildings. Within academic realms, ongoing research continues to yield results in the engineering design, production, and construction phases of prefabricated buildings[2]. Nevertheless, scientific exploration and research delineating the forefront and evolutionary trends of construction safety in prefabricated buildings remain relatively scant. Thus, utilizing CiteSpace, this study analyzes relevant literature in databases, offering an interpretation of the current research status in a scientific knowledge mapping format. Integrating focal analyses of key literature, it delineates the associated research framework and hotspots, culminating in an in-depth systematic summary and analysis, with the ultimate aim of providing guidance and recommendations for theoretical research and practical application within the realm of construction safety for prefabricated buildings.

2. Research Methods and Data Sources

Visualization analysis is a method developed by sociologists based on mathematical techniques, graph theory, and quantitative analysis[3]. Common information visualization analysis software includes Arnet Miner (expert retrieval system), Paper Lens (data relationship mining), TDA (Thomson data analysis), and CiteSpace, among others[4]. In comparison with other software, CiteSpace integrates cluster analysis, social network analysis, multidimensional scaling analysis, and focuses on detecting and analyzing the evolutionary trends of research frontiers,

understanding the relationship between research frontiers and their knowledge base, as well as the internal connections among different research frontiers.

CiteSpace, a visualization analysis software, creates visual knowledge maps to study the network relationships of literature related to construction-phase projects in architectural engineering, linking macro-scale networks with micro-scale nodes to explore underlying causes that have not been consciously recognized, thus detecting research hotspots and frontiers in this field[5].

This study utilized a method combining bibliometrics and social network analysis (SNA), using the CNKI and Web of Science databases to analyze relevant literature from 2015 to 2024. Relevant papers on the topics of "prefabricated buildings" and "construction safety" were retrieved, and data files that were beyond the scope of this study or had redundant content, as well as any literature not meeting the research criteria, were removed. After the screening process, the results were visualized to reveal the hotspots and developmental directions in the field of construction safety of prefabricated buildings, in China and internationally, as represented in Figure 1.

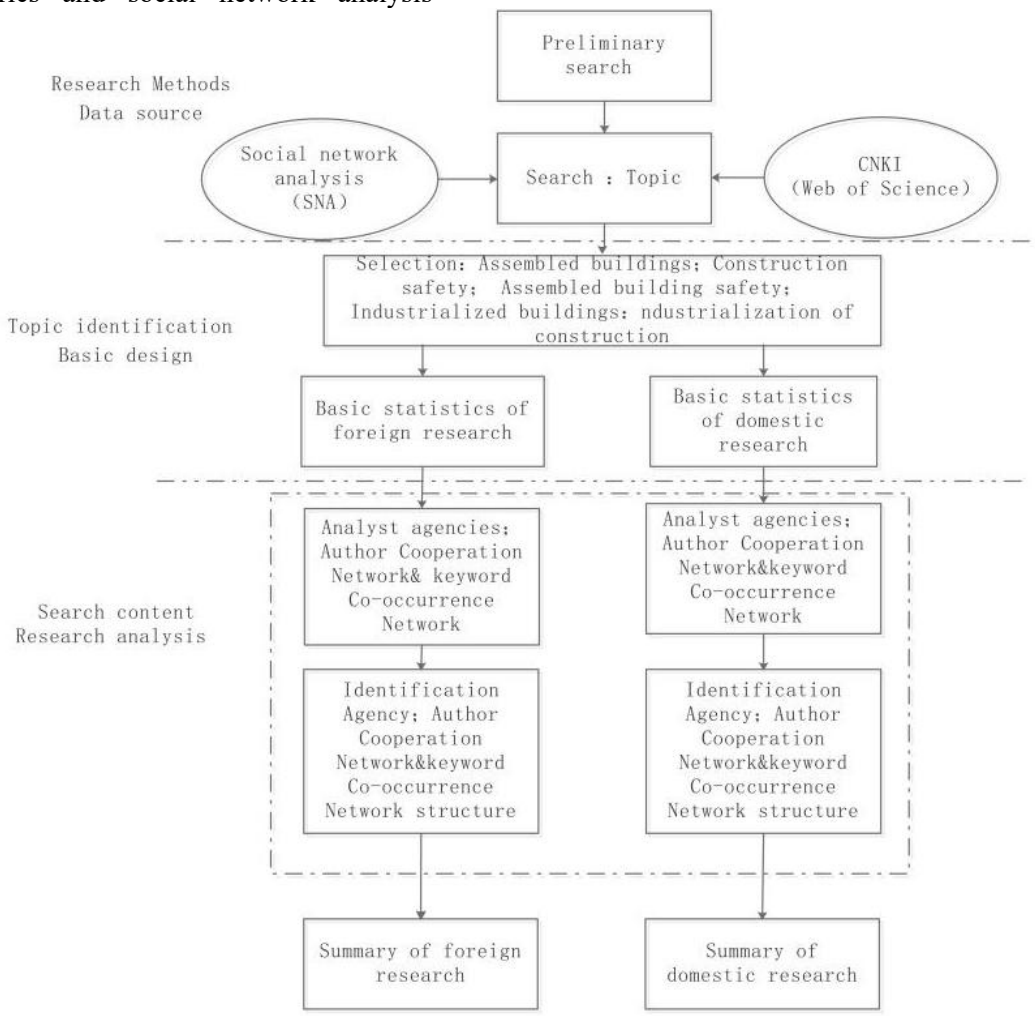

Figure 1. Visualization Analysis Research Framework

3. Analysis of Characteristics in Research on Global Prefabricated Building Construction Safety

Utilizing the CiteSpace software, this study conducted research and analysis on keywords, co-authorship, and institutional cooperation in this field. Foreign language data, using "prefabricated building + construction safety" and "Construction is safe for industrial construction" as search keywords, underwent multiple advanced searches on CNKI. Ultimately, all journals, as well as journals from SCI, EI, Peking University Core Collection, CSSCI, CSCD, and other sources, were collected. After a manual screening

process, irrelevant and incomplete documents were removed, resulting in a total of 1,960 valid records.

The data in Refworks format collected from CNKI was then transformed into a format suitable for CiteSpace analysis using the Web of Science (WOS) data source. This data was subsequently imported into CiteSpace for statistical analysis and the creation of a scientific knowledge map, with corresponding parameters set as illustrated.

3.1 Author Network Analysis

Selecting "Author" as the node type and setting the threshold in the software's internal panel "Node Labels" to 3, clear visualization results were obtained, resulting in an author network map as shown in Figure 2.

Figure 2. Global Author Network Mapping

A total of 262 nodes (authors) and 262 edges (collaboration relationships) were obtained, with a density of 0.0051. The data from the knowledge mapping shows a low density of co-occurrence networks among authors in the research field, indicating that authors tend to conduct independent research with relatively few connections among them. The overall research field appears to be in a fragmented state, with collaboration relationships not yet being sufficiently close to form large-scale research teams. There are relatively few contacts among scholars, and a mature core area has not yet formed. Among them, George Qhuang and Fang Ji have more connections with other authors, indicating signs of research teams led by these two authors. The remaining authors have not formed fully-fledged collaborative teams.

The size of the nodes in the knowledge mapping represents the different publication frequencies of the authors. The larger the node, the higher the publication frequency of the author[6]. By clicking on the "Network Summary Table", publication frequency information of the authors can be obtained. After sorting and organizing the data, it was found that in 2015, there were 9 papers related to construction safety of prefabricated buildings. From 2017 to 2019, the number of foreign papers on construction safety of prefabricated buildings gradually increased, with many of them authored by Chinese researchers. This indicates that in recent years, China has made significant contributions to research in the field of construction safety of prefabricated buildings. The publication trend from 2015 to 2024 is shown in Figure 3, with a sharp increase in research papers in this field from 2016 to 2019. The number of papers remained around 38 from 2019 to 2022. These data indicate that construction and safety management in the field of prefabricated building construction have become topics of increasing interest and research focus in recent years.

3.2 Institutional Network Analysis

By selecting "Institution" under Node Types and adjusting the internal panel settings, the institutional knowledge mapping was generated, as shown in Figure 4.

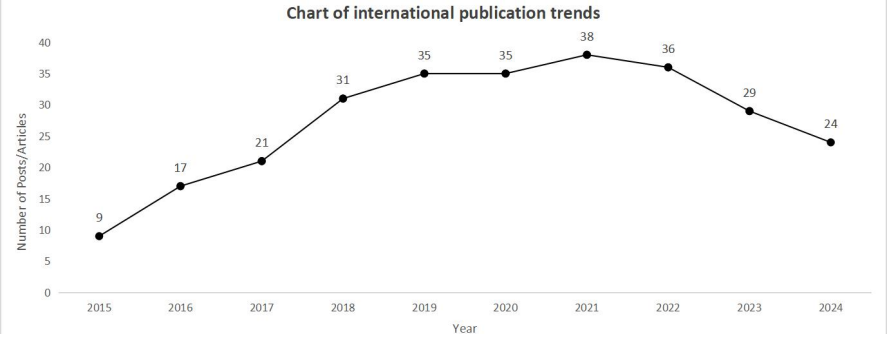

Figure 3. Number of Papers Published from 2015 to 2024

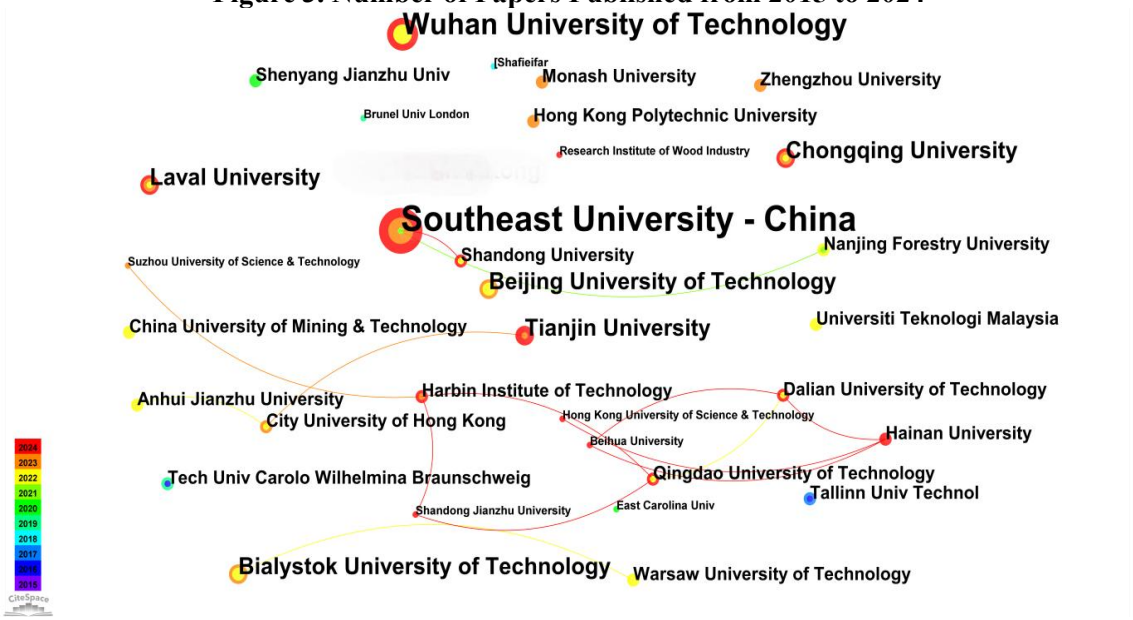

Figure 4. Overlapping Institutional Network Mapping

The analysis identified 178 nodes (institutions) and 127 connections (collaborations), with a network density of 0.0081. This indicates that the co-occurrence network between institutions is moderate, suggesting that institutional collaborations in this research field are not particularly strong, with many one-time partnerships. The data also highlights the presence of numerous industry-academia collaborations in this field. For instance,

Southeast University-China has collaborated with Shandong University, Tianjin University, Qingdao University of Technology, and other academic institutions, demonstrating the substantial support of practical projects within this research domain.

3.3 Hotspot Distribution in Research Fields

By selecting "Keyword" under Node Types, 218 nodes (keywords) and 327 connections (co-occurrence relations) were identified, with a density of 0.0138. Setting the Threshold in Node Labels to 4 resulted in a clear visualization, revealing the main keyword co-occurrence knowledge mapping, as shown in Figure 5.

Keywords distill the core content of papers, reflecting the authors' primary perspectives and academic thoughts[7]. Tracking keywords allows for an understanding of the development focus of the literature[8]. In the figure, the node for the keyword "construction" is the largest, with a frequency of 42, indicating that it is the most prominent topic in the research field of prefabricated building construction. The industrialized construction method demands high precision in execution, leading to numerous technical and management challenges in construction, making it a critical area needing breakthroughs in the industry.

Other significant keywords, in order of node size, include "design", "safety", "performance", "behavior", and "model". This is due to the complex nature of prefabricated building construction, which involves aspects such as detailed design, behavioral patterns,

construction methods, and material types. Additionally, due to the unique characteristics of prefabricated construction, safety management has gradually become a research hotspot.

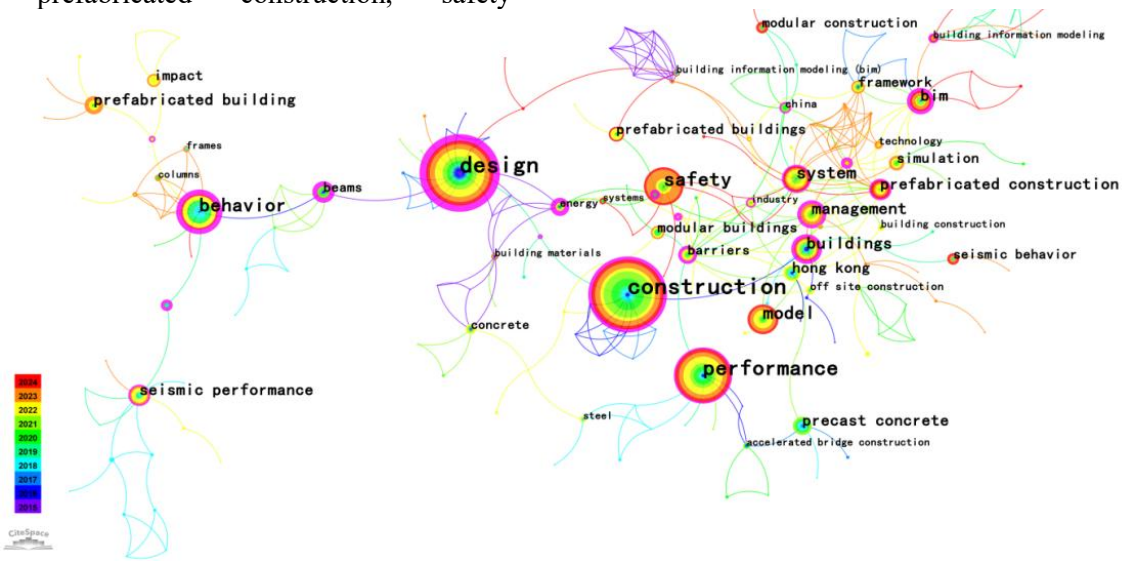

Figure 5. Main Keyword Knowledge Mapping

Smaller keyword nodes include "displacement", "cost", "energy", and "mechanical property". Although researchers have consistently studied issues related to cost, energy, and mechanical performance, the widespread application of scientific research often requires the support of technological advancements and policy environments[9]. By accessing the Network Summary Table, detailed parameters of the keywords were obtained, and the top 10 keywords by frequency are listed in descending order in Table 1.

Table 1. Keyword Frequency

Frequency	Centrality	Year	Keyword
42	0.24	2016	construction
39	0.62	2015	design
32	0.15	2016	performance
21	0.42	2016	behavior
18	0.02	2020	model
15	0.19	2019	system
13	0.22	2020	management
12	0.2	2017	bim
11	0.03	2017	precast concrete
11	0.14	2021	prefabricated construction

3.4 Hotspot Clustering Analysis of High-frequency Keywords

By selecting "Extract Cluster Keywords" and choosing "Use Keywords", and then comparing clustering methods LLR and LSI, the LLR clustering method was chosen. The clustering mapping of all keywords in this field is shown in Figure 6.

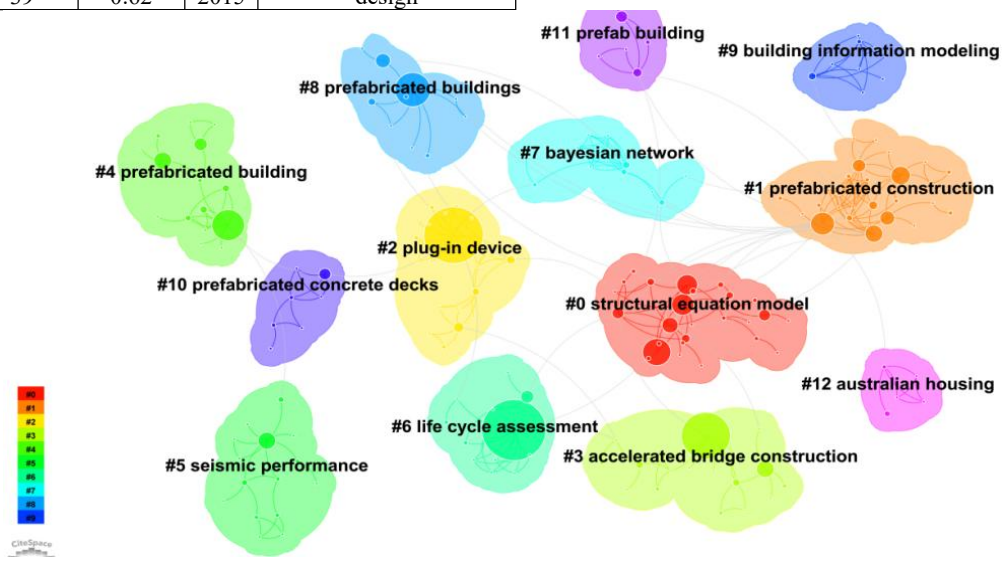

Figure 6. Keyword Clustering Mapping

The keyword clustering mapping reveals the different research focal points within the field[10]. There are 13 clusters represented by labels, numbered from #0 to #12. The larger the cluster number, the fewer keywords it contains; conversely, the smaller the number, the more keywords it includes[9]. The cluster labels are: #0 structural equation model, #1 prefabricated construction, #2 plug-in device, #3 accelerated bridge construction, #4 prefabricated building, #5 seismic performance, #6 life cycle assessment, #7 bayesian network, #8 prefabricated buildings, #9 building information modeling, #10 prefabricated concrete decks, #11 prefab building, #12 australian housing. From the co-occurrence mapping, it is evident that due to the seismic performance of prefabricated buildings, design research keywords dominate. Additionally, building information modeling (BIM) is a key area of focus in the development of industrialized construction. There is noticeable overlap between clusters, and construction safety, which falls under cluster #1, highlights the prominence of research on the construction process. After sorting the data, a summary of the centrality of the nodes (keywords) is presented in Table 2.

Table 2 Clustering Keyword Frequency

Label	Frequency	Centrality	Earliest Year	Scale
0	27	0.951	2019	structural equation model; influencing factor; prefabricated construction; prefabricated construction risks; assembled building
1	26	0.952	2021	prefabricated construction; decision making; construction risk management;
2	20	1	2017	deck-to-girder connection; life cycle thinking (lct); quasi-static cyclic loading test
3	18	0.927	2018	accelerated bridge construction; precast concrete; performance; microstructure;
4	16	0.974	2021	prefabricated building; fire tests; intelligent construction; applied element method
5	15	0.941	2019	seismic performance; functional polymers; anchoring strength; segmental column
6	14	0.973	2018	life cycle assessment (lca); thermal behavior; nondestructive testing (ndt); settlement phenomena
7	12	0.898	2018	bayesian network; improved human factor analysis and classification system; cognitive model; unsafe behaviors;
8	10	0.907	2022	prefabricated buildings; bayesian networks; visual marker -based metrology;
9	9	0.995	2020	building information modeling; artificial intelligence; engineer-to-order manufacturing; warehouse;
10	7	0.983	2018	prefabricated concrete decks; precast construction; plastic hinge; ductility
11	6	0.99	2019	prefab building; building information model (bim); building envelope; analytic network process (anp)
12	5	0.995	2020	australian housing; off-site manufacturing; leagile strategies;

The table reveals that in 2017, the keywords were concentrated on "quasi-static cyclic loading test" and "quasi-static cyclic loading test", both focusing on the study of Structural performance. From 2018 to 2019, keywords such as "lifecycle assessment", "design", and "construction methods" emerged, indicating a growing focus on design and technical issues in the construction process. Starting in 2019, keywords like "australian housing" and "building information modeling" began to appear, reflecting that prefabricated construction had entered the stage of informatization and intelligent research.

3.5 Keyword Burst Chart

By clicking on "Burstness" in the Control Panel of the software, the keyword bursts in the field of Materials Science were extracted, ranked by burst intensity, and the time periods for each burst keywords were summarized. The top 25 keywords with the highest burst intensity from 2015 to 2024 were extracted, and the results are visualized in Figure 7.

The keywords "buildings" and "hygrothermal performance" first appeared in 2016 and persisted for a period, indicating that 2016 to 2018 was the early developmental phase of precast concrete, highlighting sustained interest during that time. Keywords like "behavior", "precast concrete", and "reinforced concrete", which have emerged since 2019, reflect various research focuses in the field of prefabricated construction. Notably, "behavior" is closely related to "safety", suggesting that construction safety has been a frontier topic in recent years. Moreover, since its appearance in 2020, it has persisted through 2024, indicating that the field of construction safety has remained a continuous focus of research and attention.

4. Visualization Analysis of Prefabricated Construction Safety Management in China

4.1 Co-authorship Mapping Analysis

In the software's parameter selection panel, the "Threshold" was set to "top10perslice",

followed by selecting "Author" in Node Types and adjusting the Threshold in Node Labels to 0 to generate a clear visualization. The resulting knowledge mapping of co-authorship is presented in Figure 8.

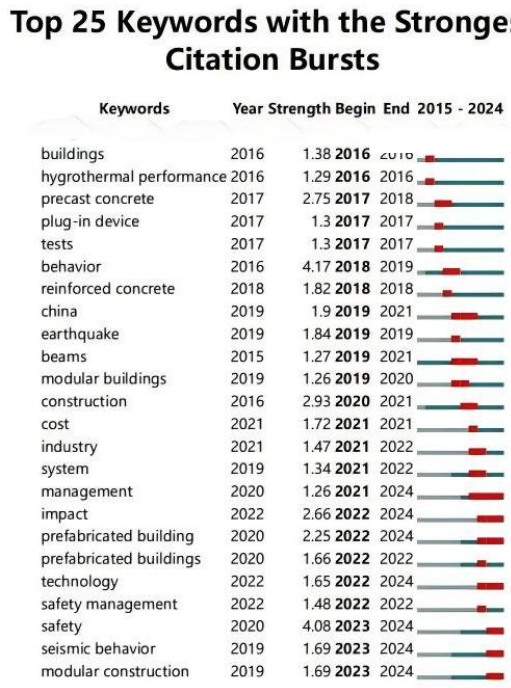

Figure 7. Visualization of Keyword Bursts from 2015 to 2024

Figure 8. Knowledge Mapping of Co-Authorships

The analysis revealed a total of 190 nodes (authors) and 111 edges (collaborations), with a network density of 0.0062. This implied that the co-occurrence network density of key authors in this research domain was relatively low, with a prevalence of single-instance collaborations. The data demonstrated that the author Chang Chunguang had engaged in extensive research in this field. Wu Xi, meanwhile, formed a small collaborative team, while the rest of the authors had not established any significant cooperative groups. The limited connections among authors indicated that co-authorship was sparse within this research field, with scholars working more independently. In terms of publication frequency, Chang Chunguang had authored more than 21 publications, indicating a substantial contribution to the literature in this area.

4.2 Institutional Mapping Analysis

In the software's parameter selection panel, the "Threshold" was set to top20perslice. Then, "Institution" was selected under Node Types, and the Threshold in Article Labeling was adjusted to 0. After clicking the Network Summary Table, the ranking of institutions by publication frequency was obtained, as shown in Table 3.

Table 3. Institutional Publication Frequency

No.	Frequency	Institution	Year
1	29	Shenyang Jianzhu University	2016
2	20	School of Management, Shenyang Jianzhu University	2017
3	14	Qingdao University of Technology	2018
4	12	School of Management Engineering, Qingdao University of Technology	2020
5	9	AnHui Jianzhu University	2018
6	7	Shenyang Jianzhu University	2018
7	6	Second Construction Co., Ltd., China State Construction Engineering	2020
8	5	School of Management Engineering, Southeast Jianzhu University	2018
9	4	Wuhan University of Technology	2017
10	4	TianJing University	2018

4.3 Hotspot Distribution in Research Fields

In the software's parameter selection panel, the "Threshold" was set to top20perslice. Then, after selecting "Node Types" as Keyword, a total of 221 nodes (keywords) and 270 edges (co-occurrence relations) were obtained, resulting in a network density of 0.0111. By selecting Keyword under Node Types and setting the Threshold in Node Labels to 6, a clear visualization was generated. The knowledge mapping of the main keyword co-occurrence is shown in Figure 9.

The node with the greatest significance is "prefabricated building construction", followed by "construction safety". Other keywords in order include "safety management", "prefabrication", "risk assessment", "analytic hierarchy process", "precast assembly", and "safety". The warmth of the node color represents the chronological

order in which the nodes first appeared. By clicking "Layout" in the Control Panel, the evolution of keyword distribution can be visualized. Accessing the "Network Summary Table" provides detailed keyword parameters, which after organization, reveal the co-occurrence frequency of keywords. The top 20 keywords by frequency, sorted in descending order, are listed in Table 4.

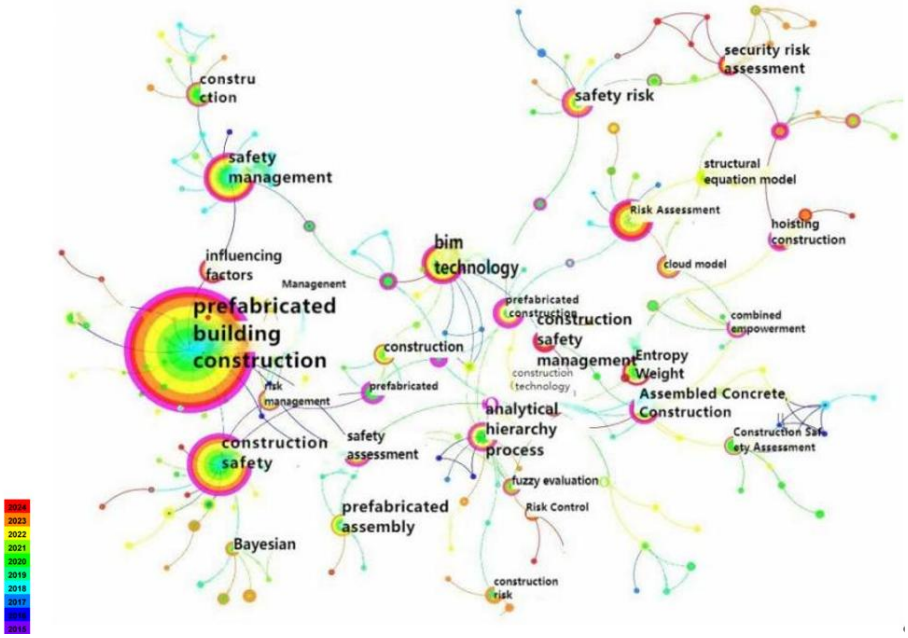

Figure 9. Knowledge Mapping of Keyword Co-occurrence in Research

Table 4. Top 20 Keywords by Frequency

No.	Freq	Centrality	Year	Core Keywords
1	425	0.62	2016	prefabricated building
2	109	0.55	2015	construction safety
3	80	0.31	2016	safety management
4	50	0.23	2017	risk assessment
5	47	0.29	2017	BIM technology
6	29	0.25	2016	analytic hierarchy process
7	27	0.25	2017	safety risk
8	23	0.19	2019	entropy weight method
9	21	0.04	2018	building construction
10	20	0.19	2017	construction safety management
11	20	0.12	2017	construction
12	20	0.58	2019	prefabricated
13	20	0.13	2018	cloud model
14	16	0.27	2019	prefabricated concrete building
15	16	0.38	2016	safety assessment
16	16	0.15	2016	influencing factors
17	15	0.04	2018	prefabricated building construction
18	13	0.1	2015	risk management
19	13	0.17	2021	safety risk assessment
20	12	0.05	2019	construction risk

The earliest appearances of core keywords, sorted chronologically, are as follows: "prefabrication" first appeared in 2016; "prefabricated building construction", "safety management", and "safety risk management" first appeared in 2018; "risk management", "precast assembly", and "construction safety" in 2021; "analytic hierarchy process" and "prefabricated building construction" in 2016; "safety risk", "construction", "risk assessment", "building technology", and "BIM technology" in 2017.From the keywords related to prefabricated building safety, it is clear that safety management primarily focuses on risk and safety assessment, and the application of BIM

technology became prominent in 2017.

4.4 High-frequency Keyword Mapping

The clustering mapping of all keywords in this field is shown in Figure 10.

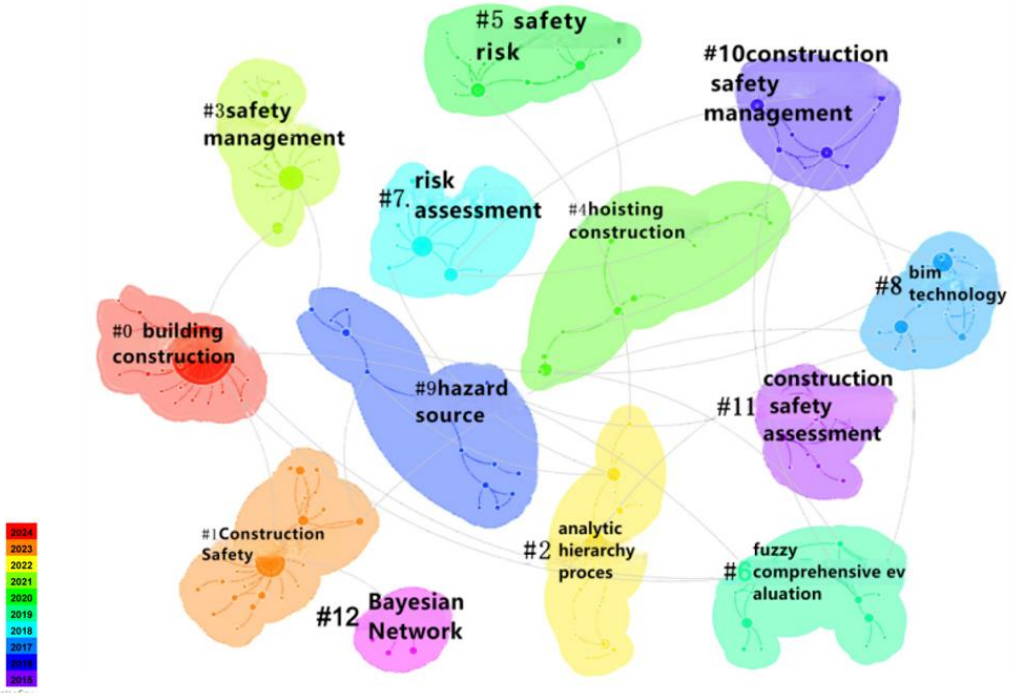

Figure 10. Keyword Clustering Mapping

The lines between nodes within a cluster represent co-occurrence relations. A higher number of connections between nodes indicates a stronger degree of co-occurrence between clustered keywords in the research topics of this field. Detailed parameters of the clusters are presented in Table 5.

Table 5. Co-occurrence Data of Clustered Keywords

Cluster Size	Cluster Number	Silhouette Value	Average Year
23	0	0.925	2019
23	1	0.995	2019
20	2	0.945	2019
19	3	0.965	2018
18	4	0.938	2020
18	5	1	2020

From the table, it is evident that the first appearance of the "prefabricated structure" cluster occurred in 2018. Around 2019-2020, there was a notable increase in hotspot keywords, along with a surge in connections between keywords, both within clusters and across clusters. After 2020, the number of connections decreased, suggesting that scholars could explore cross-cluster thematic areas for extended research, providing new entry points for current studies.

4.5 Keyword Burst Chart

The keyword bursts in Figure 11 represent keywords that saw a sudden surge or decline in frequency within this field. From the burst chart, it is evident that between 2015 and 2020, "prefabrication" was frequently mentioned, aligning with government policies strongly promoting industrialization in construction, leading to extensive research on the concept of prefabrication. Between 2018 and 2019, research on prefabricated buildings construction became more in-depth, with a growing body of literature focusing on prefabricated structures and construction techniques. From 2016 to 2018, studies on prefabricated safety management gradually increased, as scholars addressed technical challenges in construction while paying more attention to the safety management of prefabricated buildings. This period saw the emergence of research on systematic safety management topics such as risk management, construction safety assessment, safety protection, and safety control. From 2020 to 2024, research on prefabricated safety management became more refined, with "hazard sources" emerging as a hot topic, indicating increased attention to this area. Scholars can use these comprehensive aspects as entry points to further enrich and innovate in their research.

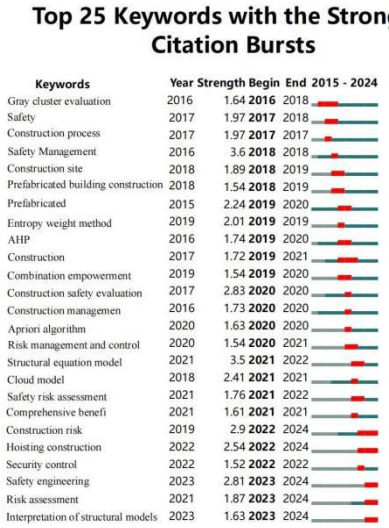

Figure 11. Keyword Burst Chart

5. Conclusion

This study, based on literature published between 2015 and 2024 with the theme of "prefabricated buildings + construction safety", utilizes the Citespace analysis tool to visualize the processed data. The visualized knowledge mapping systematically and accurately reveals the current state, key research topics, and evolving trends within this field. The primary findings are as follows:

1) Research on the construction safety of prefabricated buildings in China has progressed through two distinct phases: slow development and rapid development. From 2015 to 2017, the research in this area grew at a relatively slow pace. However, beginning in 2018, a significant surge in research output occurred, reflecting its rise as a research hotspot. Despite the increased volume of publications, the research remains in its early stages. The primary research areas, based on journal and literature distribution, are focused on construction technology, factor analysis, and safety evaluation. However, there is a notable lack of studies addressing safety design and the later operational and maintenance phases of prefabricated buildings.

2) As BIM technology and engineering management practices continue to advance, research in this domain is expected to become more specialized. High-level applications such as "BIM + IoT", "BIM + cloud computing", and "BIM + GIS" will be increasingly integrated, enabling comprehensive construction simulation. Emerging technologies like AR and VR will also see widespread adoption. The high degree of digitalization in construction industrialization will contribute to more standardized and safer prefabricated components. BIM will become increasingly intertwined with prefabricated buildings, leading to a fully matured lifecycle management model for these structures.

3) Given the aging labor force in China, the application of AI-powered robots has become a key focus of national research. The integration of AI robotics in the construction of prefabricated buildings is expected to significantly reduce the dependence on manual labor, thereby enhancing the control over construction progress and precision. This will, in turn, improve the overall safety and efficiency of prefabricated building projects.

Acknowledgments

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