

## Review Article

# A Review and Scientometric Analysis of Global Research on Prefabricated Buildings

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Prefabricated building has become one of the most significant research directions in the architecture, engineering, and construction (AEC) industry and has attracted a large number of scholars and practitioners in recent years. However, few studies have conducted a systematic review on the development of prefabricated building research around the world. In this study, the scientometric method is used to analyze the literature on prefabricated buildings in the past ten years through analysis of co-authors, co-words, and co-citation. From the Web of Science (WOS) core collection database, a total of 1224 articles were collected for statistics and analysis. The analysis results indicated that Bruno Dal Lago obtained the maximum number of co-citations, and the most significant country/region and research institution in prefabricated building research were China and Tongji University, respectively. It was also found that engineering, civil engineering, and construction and building technology were the top three subject categories that prefabricated building research belonged to. Among all the keywords of the collected articles, citation bursts were received by “cladding panel,” “precast concrete,” and “project.” Moreover, there were 11 co-citation clusters identified from the articles, and their themes included precast structures, waste management, progressive collapse, delay, precast facades, carbon reduction, laser scanning, and prefabricated residential building. This paper is expected to provide researchers and practitioners in this field a detailed and in-depth understanding of the trend and status of global research on prefabricated buildings.

## 1. Introduction

Increasing carbon emissions by human activities are leading to rising global temperatures, which results in serious global environmental problems and needs an urgent social response [1]. All aspects of human activities are gradually leading to an increase in carbon emissions. Among them, the energy use during building operations accounts for a quarter of the total CO<sub>2</sub> emissions [2]. The adoption of prefabricated buildings can effectively reduce the carbon emissions generated during the entire life cycle of buildings. Prefabricated buildings are usually constructed in two steps: off-site prefabrication and on-site installation. Off-site prefabrication is the manufacturing process that makes various

materials joined together in a specialized facility to form prefabricated components, and on-site installation is the process that installs all the individual components on-site [3]. Compared to traditional ways of construction, prefabricated buildings have a series of advantages in the project life cycle including reduction of required labor [4], savings of construction time and cost [5], decrease of construction pollution [6], ease to maintain and repair, and better convenience to dismantle and rebuild. Due to the aforementioned advantages, prefabricated buildings have been widely adopted worldwide. Many countries/regions are promoting the development of prefabricated buildings to varying degrees according to their current statuses of economic development, resources, and energy.

There have been some research efforts to review literatures on prefabricated buildings from various perspectives. Some studies focused on the management of prefabricated buildings. For example, Li et al. [7] reviewed the literature on the management of prefabricated construction (MPC) and identified the popular research areas in the field of MPC. Wang et al. [8] properly classified existing studies on precast supply chain management to reveal the research gaps and suggest research opportunities in the future. Wuni and Shen [9] found the complex nature of the barriers which hindered the wider diffusion of modular integrated construction (MIC) in the construction industry. Some researchers studied the adoption of prefabricated buildings in specific countries/regions. For example, Navaratnam et al. [10] came to the conclusion that the systems and constructions of prefabricated buildings held high potentials to sustainably enhance the efficiency and performance of the Australian construction industry. Jaillon and Poon [11] discussed the evolution of precast technology in high-rise residential developments in Hong Kong and verified that the advancement of prefabrication techniques could significantly contribute to economic and environmental benefits. Some other researchers studied the adoption of prefabrication techniques for buildings of specific functions or structural systems. For example, Newton et al. [12] studied the use of prefabrication for Australian school buildings and prefabricated learning environments. Bukauskas et al. [13] carried out a review on the prefabrication developments in whole timber construction and recommended that the focus of future research would be scaling timber structural applications and developing new digital technologies for prefabrication.

There are also some researchers focusing on the life cycle performance and seismic performance of prefabricated buildings. For example, Kamali and Hewage [14] investigated the environmental performance of modular facilities throughout the life cycle and discussed on the benefits and challenges of the modular construction method. Bofo et al. [15] clearly characterized the levels of prefabrication and investigated the performance of modular prefabrication with a dynamic case study-based review. Kurama et al. [16] reviewed the advances of prefabrication including practical applications and code developments and concluded that it was feasible with the widespread use of precast concrete in seismic regions. Jin et al. [17] critically reviewed the literature on off-site construction and its environmental performance and concluded that the two most significant challenges for the evaluation of the environmental performance of off-site built facilities were the system boundary and data accuracy. Xu et al. [18] presented a review of the applications of active hollow slabs in building systems to reduce energy utilization. Some recent studies also reviewed the applications of new technologies or innovative methods for prefabrication. For example, O'Hegarty and Kinnane [19] reviewed a large number of studies on the sandwich panels' structural performance and highlighted that it was necessary to further validate the design of novel sandwich panels and test the performance of different types of connectors. Vähä et al. [20] studied the various potential sensor technologies that could

automate building construction such as the robotics technology.

Despite of the aforementioned literature reviews on prefabrications, all of the existing reviews are focused on only a certain perspective of prefabrications such as supply chain management, energy performance, or structural design and performance. There is a lack of review that presents a high-level overview of global research trends on prefabricated buildings. Despite of some recent review papers [21, 22], these papers were mainly focused on articles before 2017. However, this field is developing rapidly, with more than 200 articles per year. There is a need to carry out a latest review and analysis of the related literature to present the most recent research trends. Therefore, this study attempted to carry out a scientometric literature review on prefabricated buildings in the recent ten years. Scientometric is a type of quantitative study to help researchers to better understand the connectivity of a certain research field [23]. The scientometric method covers comprehensive analyses of all aspects of literature such as subjects, keywords, journals, authors, institutes, and citations [24]. This article will use the scientometric research method to visually analyze and discuss the recent literature on prefabricated buildings to present the recent research trend and status. The rest of this paper is organized as follows. Section 2 presents the research method of this study. Then, the scientometric analysis results are presented and discussed in Section 3, and Section 4 discusses and recommends future research directions. Lastly, Section 5 summarizes and concludes this study.

## 2. Method

This study utilized the science mapping method to conduct a comprehensive analysis of global research on prefabricated buildings. Science mapping is a process of producing domain analysis and visualization [25] and consists of bibliometric analysis and scientometric analysis. Based on bibliometric tools and data, science mapping offers a broader approach to analyzing the literature and identifying potentially insightful patterns and trends of the domain [26]. This study adopted a three-step literature review approach including (1) bibliographic retrieval, (2) scientometric analysis, and (3) discussion as follows.

*2.1. Bibliographic Retrieval.* The first step was the bibliographic search in the Web of Science (WOS) core collection database, which contains the most valuable and influential journals all over the world [27]. Relevant literature on prefabricated buildings was searched from the database based on the topic. The searched topic was 'TS = (prefabricated or prefabrication or precast) and TS = building.' In other words, the topic of a search result must contain at least one of the three words (prefabricated or prefabrication or precast) as well as the word of building. Other similar keywords, such as "modular building," "prefabricated construction," "industrialized building," "off-site construction," and "modular construction," were also used for document retrieval. Among all the search results, conference

papers, book reviews, and editorials were excluded. Only journal articles were used for analysis because journal papers could display more comprehensive and valuable contents than other types of publications [28, 29].

In addition, the language of literature was limited to English. The remaining literature was further screened based on the subject categories. Among all the categories, categories with more than ten documents and closely related to the AEC industry were selected. On the contrary, categories that were not relevant to prefabricated buildings (e.g., biology, medicine, and agriculture) were excluded. Based on the above search and screening, research documents on prefabricated buildings were identified. As a complete literature database has not yet been formed in 2020, this study did not include literature in 2020. The number of research documents by publication year is shown in Figure 1, spanning from 1990 to 2019. Considering that the number of documents had increased significantly since 2010 (339 papers from 2000 to 2009 and 1224 papers from 2010 to 2019) and this study aimed to analyze the recent research trends, only the documents published from 2010 to 2019 were selected and analyzed. Therefore, a total of 1224 journal articles from 2010 to 2019 were selected for the following scientometric analysis in this study.

**2.2. Scientometric Analysis.** The second step is to use CiteSpace [30] as a scientific measurement and analysis tool to analyze the documents selected in the first step. CiteSpace is a tool for science mapping visual analysis [25] and is able to analyze a specific knowledge domain such as to identify the main research areas and the links between them [31]. CiteSpace can systematically generate various accessible graphs and enable scholars to visually study the hot spots in their respective fields and the relationship between research results [30]. Therefore, CiteSpace (version 5.7.R1) was used to analyze the literature of prefabricated buildings, based on Windows 10 and Java \_ 1.8.0 261-b12 platform. The relevant software parameter settings are displayed in the left top corner of each figure. The scientometric analysis conducted in this study included co-author analysis, co-word analysis, and co-citation analysis, which are presented in Sections 3.1 to 3.3, respectively.

**2.3. Discussion.** The follow-up discussion aimed to provide an in-depth interpretation and discussion of the results of scientometric analysis. For each of the three analyses (co-author analysis, co-word analysis, and co-citation analysis), the discussion is presented after the analysis in Section 3.1 to 3.3, respectively. Furthermore, an overall discussion and recommendation for future research will be presented in Section 4.

### 3. Scientometric Analysis and Results

**3.1. Co-Author Analysis.** Co-author analysis aims to investigate the literature authors and their relationships including the productivity of authors and institutions and co-

authorship network, as well as network of institutions and countries/regions based on the bibliographic records.

**3.1.1. Network of Co-Authorship.** Based on the statistical analysis of the selected journal articles, the most productive authors in the field of prefabricated buildings were identified. As shown in Table 1, the top 11 most productive authors had published at least seven journal articles. Bruno Dal Lago (Polytechnic University of Milan) was ranked as the most productive author with 14 published articles. Among all the top 11 authors, four of them were from Italy, three of them were from Hong Kong, two of them were from Mainland China, and the remaining two were from South Korea and England, respectively.

As shown in Figure 2, the co-authorship network is composed by a number of nodes and links. The nodes indicate authors and the links between different authors indicate their collaborations established by co-author relationships. Here, the co-authorship network included 372 nodes and 317 links. In the network, the node size indicates the number of publications of this author, and the thickness of a link represents the closeness of collaboration between two authors in a given year. The links' colors (from dark color to light color) represent different years from 2010 to 2019.

According to Figure 2, several closed-loop circuits could be found in this network of co-authorship, indicating a strong network of collaboration between the authors within the closed-loop circuits. The three most prominent closed-looped circuits include (1) the circuit of Bruno Dal Lago, Giandomenico Toniolo, Fabio Biondini, etc., (2) the circuit of Gennaro Magliulo, Marianna Ercolino, Andrea Belleri, etc., and (3) the circuit of Geoffrey Qiping Shen, Peng Wu, Chao Mao, Wei Pan, Guiwen Liu, etc. Based on the graph theory, Freeman's betweenness centrality is defined as the ratio of the shortest path between two nodes to the sum of all such shortest paths [32]. Freeman's betweenness centrality can connect more than two groups with nodes in-between. As shown in Figure 2, four authors achieved corresponding betweenness centrality, included Fan Xue (centrality = 0.01), Wei Pan (centrality = 0.01), Weisheng Lu (centrality = 0.01), and Xi Chen (centrality = 0.01). Moreover, citation bursts could show a surge of citations of publications and represent remarkable growth in citations through a short time period. The burst strength value is calculated based on the algorithm in Citespace. Only one author got a citation burst, which is Bruno Dal Lago (burst strength = 3.27, 2017–2019). It is also found that the research circuit of Geoffrey Qiping Shen, Peng Wu, Chao Mao, Guiwen Liu etc. had a higher number of articles from 2018, and most of the articles of this research circuit are published by Chinese researchers.

**3.1.2. Network of Countries/Regions and Institutions.** To explore the research contributions on prefabricated buildings from different countries/regions and institutions, a research power network was generated. In total, the research network included 400 nodes and 648 links. As there were too many nodes and links, the minimum threshold for analysis

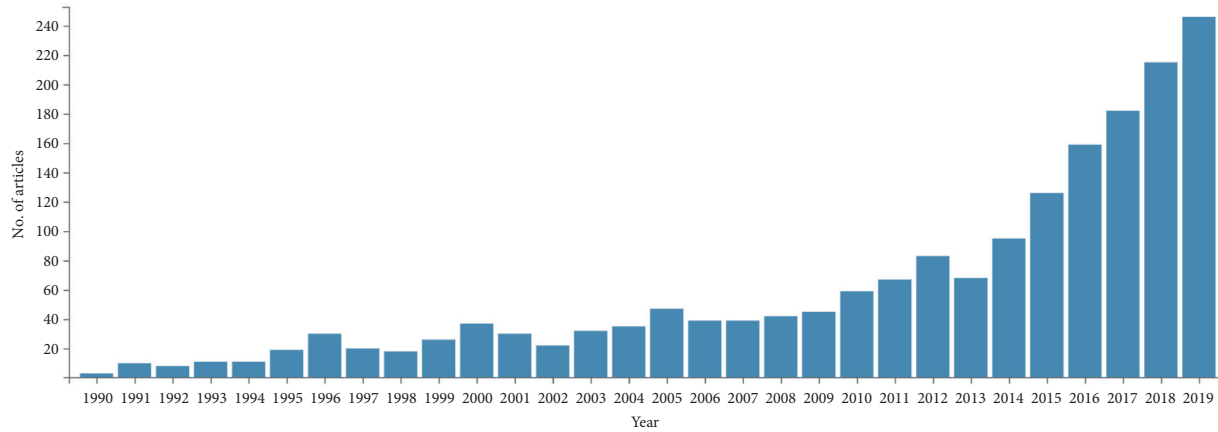


FIGURE 1: The number of articles on prefabricated buildings from 1990 to 2019.

TABLE 1: Top 11 authors with high productive.

Author	Institution	Country/ region	Count	Percentage
Bruno Dal Lago	University of Insubria	Italy	14	1.14
Geoffrey Qiping Shen	Hong Kong Polytechnic University	China	10	0.88
Giandomenico Toniolo	Polytechnic University of Milan	Italy	9	0.8
Won-kee Hong	Kyung Hee University	South Korea	9	0.8
Fan Xue	The University of Hong Kong	Hong Kong	9	0.8
Roberto Nascimbene	European Centre for Training and Research in Earthquake Engineering (Eucentre)	Italy	8	0.7
Chao Mao	Chongqing University	China	8	0.7
Gennaro Magliulo	University of Naples Federico II	Italy	8	0.7
Wei Pan	The University of Hong Kong	Hong Kong	8	0.7
Marianna Ercolino	University of Greenwich, London	England	7	0.62
Weisheng Lu	The University of Hong Kong	Hong Kong	7	0.62

was set to 7 articles. As shown in Figure 3, the node size in the network indicates the number of articles published from 2010 to 2019. A large number of countries/regions have made contributions to the articles on prefabricated buildings. According to the number of articles, all the countries/regions were divided into the following echelons: the first echelon with more than 100 articles included China (301 articles), the USA (197 articles), Italy (157 articles), and Australia (103 articles); the second echelon with 51 to 100 articles included England (78 articles), South Korea (57 articles), and Spain (54 articles); the third echelon with 31 to 50 articles included Turkey (44 articles), Canada (41 articles), and Germany (32 articles); the other countries/regions contributed no more than 30 articles in this research field. The large numbers of publications from the aforementioned countries/regions indicated that these countries/regions were active and advanced in prefabrication building research. The lead of China in this research field is not surprising due to the strong pushes from the Chinese government. To address construction-induced pollutions, the Chinese government has recently been promoting the modern prefabricated buildings in the long-run national development plans as well as short-run industrial policies

[33]. Therefore, strong efforts from both the academia and industry have been made on prefabricated buildings in China, leading to the fast growth of prefabricated building research. In addition, the network also implied research collaborations between different countries/regions. It is found that researchers from China have been actively collaborating with researchers from other countries/regions, such as the USA, Australia, Malaysia, Japan, South Korea, England, and Singapore. There were also some other groups of countries/regions with strong collaborations such as the group including Italy, Germany, Switzerland, and Sweden and the group including Brazil, Turkey, Spain, and Canada.

The contributions of institutions were also identified in Figure 3. A total of 18 institutions had at least 10 articles published on prefabricated building research including Tongji University (36 articles), Hong Kong Polytechnic University (35 articles), University of Hong Kong (28 articles), Southeast University (24 articles), Politecnico di Milano (23 articles), Chongqing University (21 articles), Shenzhen University (19 articles), Curtin University (17 articles), University of Naples Federico II (15 articles), Tsinghua University (14 articles), Kyung Hee University (14 articles), Harbin Institute of Technology (13 articles), Tianjin





FIGURE 2: Co-authorship network and link colors corresponding to years 2010–2019.

University (13 articles), University of Auckland (11 articles), University of Canterbury (11 articles), University of Melbourne (11 articles), Beijing University of Technology (11 articles), and Beijing Jiaotong University (10 articles).

In Figure 3, the purple rings represent nodes with high betweenness centrality values of countries/regions and research institutions. The top countries/regions included the USA (centrality=0.68), England (centrality=0.45), China (centrality=0.40), Canada (centrality=0.27), Italy (centrality=0.24), Austria (centrality=0.17), Turkey (centrality=0.15), Australia (centrality=0.14), South Korea (centrality=0.13), and Brazil (centrality=0.11), and the top institutions included Hong Kong Polytechnic University (centrality=0.11), Korea Advanced Institute of Science & Technology (centrality=0.10), Southeast University (centrality=0.06), and University of Hong Kong (centrality=0.05). These countries/regions and institutions have substantially contributed to the research activities and network of prefabricated buildings.

Furthermore, some countries/regions received high citation bursts which represent significant growth in citations over a certain time period, as shown in Table 2. Several research institutions received high citation bursts as well, as presented in Table 3. These high citation bursts show that these countries/regions or research institutions had received a great amount of attention on prefabrication building research. Citation bursts were distributed in North and South

America, Asia, Europe, and Africa, indicating that research of prefabricated buildings has attracted worldwide attention in the past decade. Moreover, Shenzhen University received high citation bursts in the last two years, demonstrating the recent popularity and impacts of its research outputs. The government policies of the area where Shenzhen University is located also have a certain impact on its research. As Shenzhen is a special economic zone in China, Shenzhen has always been a pioneer in experimenting and implementing new policies including the adoption of prefabricated buildings [34].

**3.2. Co-Word Analysis.** Research efforts on prefabricated buildings have been made on different topics and subjects. Co-word analysis can help researchers to understand the popularity and frontiers of prefabricated building research.

**3.2.1. Co-Occurring Subject Network.** Every journal has a list of corresponding subject categories. The subject categories of all articles imported from the WOS database can form the co-occurring subject network of prefabricated building research. As shown in Figure 4, a total of 108 nodes and 408 links were generated to analyze the emerging trends on subject categories. The larger the size of each node, the more the numbers of articles of the category. The subject categories with the most articles included engineering (911

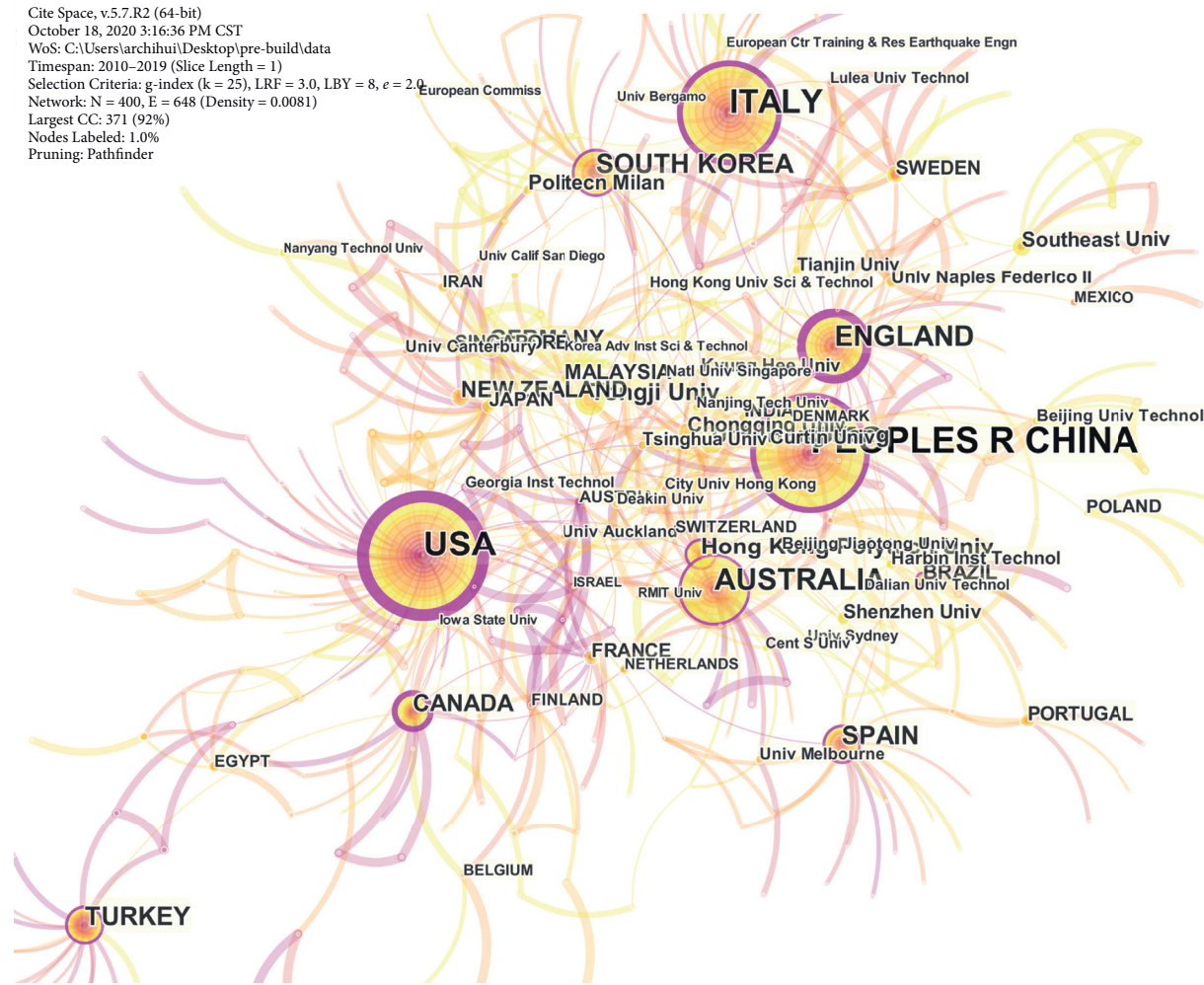


FIGURE 3: Network of countries/regions and institutions.

TABLE 2: Top nine countries/regions with the strongest citation bursts.

Country/region	Strength	Begin (year)	End (year)
USA	3.7804	2011	2012
Slovenia	4.2532	2010	2013
South Korea	2.5137	2012	2012
Sweden	3.0426	2013	2015
Turkey	3.6344	2013	2013
Scotland	3.0426	2014	2015
Mexico	2.8849	2014	2015
Taiwan	2.4231	2015	2016
Egypt	2.5588	2015	2016

articles), civil engineering (692 articles), construction and building technology (499 articles), materials science (211 articles), multidisciplinary materials science (149 articles), environmental science & ecology (129 articles), engineering geology (121 articles), science and technology (120 articles), environmental sciences (119 articles), and green and sustainable science & technology (100 articles). Some categories with small amounts of articles were also closely related to

TABLE 3: Top four research institutions with the strongest citation bursts.

Research institution	Strength	Begin (year)	End (year)
Lulea University of Technology	2.5195	2013	2015
Tongji University	2.8136	2017	2019
The University of Sydney	2.6405	2017	2019
Shenzhen University	2.8017	2018	2019

prefabricated buildings, such as architecture (46 articles), computer science (39 articles), and management (12 articles). The colors of the links represent the corresponding years from 2011 to 2019, similar to Figure 2. The number of articles with subject categories of construction and building technology, environmental science and ecology, engineering geology, computer science, green and sustainable science and technology, and manufacturing engineering had substantially increased in the past five years.

As shown in Figure 4, subject categories with purple rings indicated high betweenness centrality. Subject



**3.2.2. Co-Occurring Keywords' Network.** Keywords usually indicate the main research contents of articles. Therefore, the network of co-occurring keywords can represent the research development on prefabricated buildings over time.



TABLE 4: Top 11 subject categories with the strongest citation bursts.

Subject category	Strength	Begin (year)	End (year)
Transportation sciences and technology	4.0585	2010	2012
Transportation	3.3969	2010	2012
Mechanical engineering	2.7214	2010	2013
Architecture	2.8017	2010	2012
Materials science, characterization, and testing	3.7124	2013	2015
Applied physics	2.7005	2017	2017
Manufacturing engineering	2.5941	2017	2017
Green and sustainable science and technology	12.8502	2018	2019
Environmental studies	2.9273	2018	2019
Environmental science and ecology	2.7965	2018	2019
Environmental science	5.8137	2018	2019

There are two types of keywords in the WOS core collection database. One type is the “author keywords,” which are provided by the authors, and the other type is the “keyword plus,” which are defined by the journals. Both types of keywords were used to build a co-occurring keywords’ network. As shown in Figure 5, a total of 425 nodes and 1276 links were included in this network.

The size of each node represents the frequency with which keywords appear in the database. The keywords with the highest frequencies included “performance” (frequency = 172), “design” (frequency = 156), “prefabrication” (frequency = 155), “behavior” (frequency = 151), “building” (frequency = 140), “construction” (frequency = 103), “concrete” (frequency = 89), “system” (frequency = 87), “model” (frequency = 84), “connection” (frequency = 73), “precast concrete” (frequency = 65) and “seismic performance” (frequency = 65). In addition, several keywords received relatively high scores of betweenness centrality including “building” (centrality = 0.14), “model” (centrality = 0.11), “wall” (centrality = 0.11), “performance” (centrality = 0.10), “behavior” (centrality = 0.10), “construction” (centrality = 0.10), “precast concrete” (centrality = 0.10), “concrete” (centrality = 0.09), “sustainability” (centrality = 0.09), “beam” (centrality = 0.09), “reinforced concrete” (centrality = 0.08), “bridge” (centrality = 0.08), “algorithm” (centrality = 0.08), “prefabrication” (centrality = 0.07), “strength” (centrality = 0.07), and “reduction” (centrality = 0.07). These keywords connected different research topics and became an indispensable role in the development of prefabricated building research. Moreover, 26 keywords obtained citation bursts, as shown in Table 5. These citation bursts indicated that these keywords stood out as the most important themes and hot topics in research of prefabricated buildings in the corresponding years.

Among all the keywords, the keyword “performance” occupied the first place in frequency and also had a high centrality, indicating that the performance of prefabricated buildings was a very important research topic. Some keywords related to prefabricated concrete buildings such as “precast concrete,” “concrete,” and “connection” were also among keywords of the highest frequency and high betweenness centrality. Keywords representing different types of structures, such as “precast concrete,” “timber structure,” and “steel,” obtained citation bursts in corresponding time periods. Moreover, the keyword “cladding panel” obtained

the highest citation burst in the last three years, becoming a hot topic in recent prefabricated building research. It is believed that the noticeable increase would not be possible without the efforts of various project stakeholders including the government [35].

**3.3. Co-Citation Analysis.** Co-citation analysis consists of journal co-citation analysis, author co-citation analysis, and document co-citation analysis. Co-citation can indicate the frequency that two documents are cited together by another document [36] and have been used for measuring the similarity among articles. Cluster analysis that can reveal the inherent relationships between different research directions is used to analyze the generation of changes of the research trends and to find the research highlights during specific time periods.

**3.3.1. Network of Journal Co-citation.** The journals that have published most prefabricated building research in the past ten years were summarized and shown in Table 6. Among the top 10 journals, Engineering Structures had published the most articles (93 articles) on prefabricated building research, followed by Automation in Construction (48 articles) and Journal of Cleaner Production (45 articles). Three out of the top 10 journals are published in America and the other journals are published in Europe.

As shown in Figure 6, the journal co-citation network consisted of 584 nodes and 1709 links. The size of node represents each source journal’s co-citation frequency. Based on the frequency, it is found that the most impactful journals were Engineering Structures (frequency = 382), Journal of Structural Engineering (frequency = 273), Construction and Building Materials (frequency = 269), PCI Journal (frequency = 265), Building and Environment (frequency = 264), Energy and Buildings (frequency = 233), Automation in Construction (frequency = 227), and ACI Structural Journal (frequency = 215). Each of the above journals has received more than 200 citations.

There was no journal with high betweenness centrality, while a total of 34 journals got citation bursts. Journals with higher citation bursts in each corresponding time period are shown in Table 7. These findings suggested that these





Keyword	Strength	Begin (year)	End (year)	Keyword	Strength	Begin (year)	End (year)
Precast concrete	4.5669	2010	2011	Precast concrete structure	2.7763	2013	2017
Algorithm	3.73	2010	2014	LCA	2.9164	2014	2015
Construction management	2.8337	2010	2012	Ductility	3.5007	2014	2016
Seismic	4.0521	2010	2016	Model	3.4382	2014	2015
Reinforced concrete	2.632	2010	2011	Experimental test	3.3648	2014	2015
Steel	2.931	2010	2014	Wood	3.3648	2014	2015
Timber structure	3.0576	2011	2015	Fiber	3.3044	2015	2016
Aggregate	2.7772	2011	2012	Methodology	2.9062	2015	2017
Construction and demolition waste	2.4548	2012	2013	Vibration	2.8314	2015	2016
Composite	2.7305	2012	2013	Framework	2.6884	2016	2017
Prestressed concrete	2.7834	2012	2015	Cladding panel	2.9062	2017	2019
Numerical analysis	3.2883	2012	2013	Technology	2.4072	2017	2019
Prefabrication	2.9345	2012	2013	Project	2.508	2017	2019

Among all the journals, the Journal of Engineering Structures had the largest number of published articles and

obtained the highest co-citation frequency, showing the highest impact on prefabricated building research. The Journal of Supply Chain Management obtained the highest co-citation burst after 2017 and became the most active and





TABLE 7: Top 12 journals' co-citation with the strongest citation bursts in each corresponding period.

Journal	Strength	Begin (year)	End (year)
Solar Energy	3.5507	2010	2012
Renewable Energy	3.4585	2010	2012
Cement and Concrete Composites	4.3234	2010	2014
Materials and Structures	4.5744	2011	2013
Journal of Information Technology in Construction	4.6662	2011	2014
Journal of Infrastructure Systems	4.0156	2012	2014
Forest Products Journal	3.7188	2013	2015
Journal of the American Concrete Institute	4.0921	2013	2016
Computers & Structures	3.2797	2013	2016
Journal of Bridge Engineering	3.8784	2015	2016
Advanced Materials Research	2.8515	2016	2019
Journal of Supply Chain Management	2.4879	2017	2019

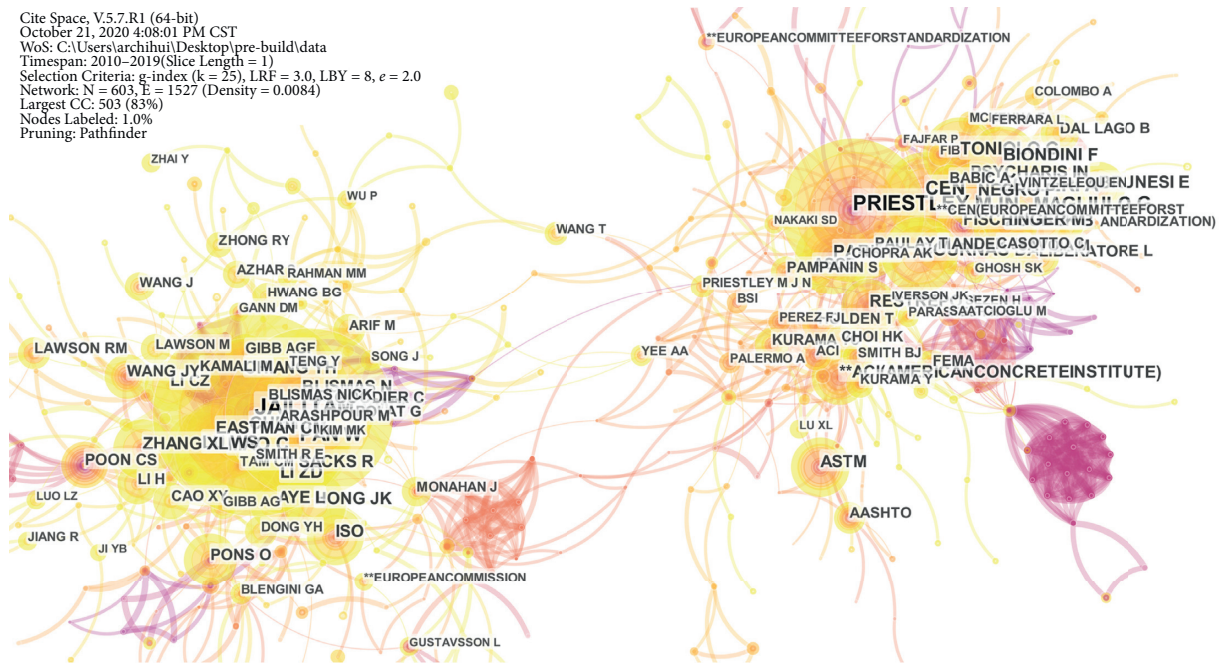


FIGURE 7: Network of author co-citation.

locations showed that prefabricated building research has been a global trend. No cited authors with high betweenness centrality were found here.

In addition, a total of 47 authors have received citation bursts. Among them, the top 16 authors are shown in Table 8. Their papers had gradually made a certain impact on the research direction of prefabricated buildings and were worthy learning and following.

Among all the authors, R. Park had one of the highest co-citation frequency and received higher citation burst, indicating the high impacts of his research. Both T. Paulay and R. Park were from the University of Canterbury, indicating that this institution was one of the most active on prefabricated building research from 2010 to 2013. Furthermore, both Nenad Čuš Babič from University of Maribor and Bruno Dal Lago from University of Insubria received high citation bursts in last three years, indicating that their research works have attracted more attention in recent years.

### 3.3.3. Network of Document Co-Citation

1) *Co-Citation Network Analysis.* Document co-citation network can be used to demonstrate the quantity and authorship of references cited by publications. The top 15 most cited documents based on the WOS citation metric are presented in Table 9. Among them, Chen et al. [37] obtained the top position with 174 citations, followed by Aye et al. [38], Pavlović et al. [39], Firth et al. [40], Mao et al. [41], Mas et al. [42], and Eastman et al. [43], each of which had more than 100 citations. The other eight documents also obtained at least 76 citations.

Document co-citations' network which consisted of a total of 924 nodes and 2287 links is presented in Figure 8. Every link between two corresponding documents represents their co-citation relationship. Each node labeled with the first author's name and the year of publication represents a document, and the node size represents the co-citation

TABLE 8: Top 16 authors' co-citation with the strongest citation bursts in each corresponding period.

Author	Strength	Begin (year)	End (year)	Author	Strength	Begin (year)	End (year)
R. Park	3.2749	2010	2013	E. N. Vintzeleou	4.2627	2013	2017
Murat Saatcioglu	4.5482	2010	2016	Abdelghani Benayoune	3.0379	2014	2015
Halil Sezen	3.8183	2010	2015	British Standards Institution (BSI)	4.2439	2014	2017
T. Paulay	4.4183	2011	2013	Chris Pantelides	3.987	2015	2016
Giovanni Fabbrocino	3.8378	2011	2014	F. J. Perez	4.5168	2015	2017
Chi Sun Poon	3.9421	2012	2015	R. M. Lawson	4.1454	2016	2017
John B Mander	4.0624	2013	2016	Bruno Dal Lago	3.2649	2017	2019
American Concrete Institute (ACI)	4.887	2013	2016	Nenad Cuš Babič	2.9694	2017	2019

TABLE 9: Top 15 most cited documents.

No.	Article	Title	Citations
1	Chen et al. [37]	Sustainable performance criteria for construction method selection in concrete buildings	174
2	Aye et al. [38]	Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules	151
3	Pavlović et al. [39]	Bolted shear connectors vs. headed studs' behaviour in push-out tests; Journal of constructional steel research	146
4	Firth et al. [40]	Between a rock and a hard place: environmental and engineering considerations when designing coastal defence structures	139
5	Mao et al. [41]	Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: two case studies of residential projects	139
6	Mas et al. [42]	Influence of the amount of mixed recycled aggregates on the properties of concrete for nonstructural use	104
7	Eastman et al. [43]	Exchange model and exchange object concepts for implementation of national BIM standards	103
8	Magliulo et al. [44]	The Emilia Earthquake: seismic performance of precast reinforced concrete buildings	99
9	Lu and yuan [45]	Exploring critical success factors for waste management in construction projects of China: resources, conservation, and recycling	97
10	Chen et al. [46]	Modelling, design, and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: part 1, BIPV/T system and house energy concept	91
11	Qu et al. [47]	Pin-supported walls for enhancing the seismic performance of building structures	84
12	Belleri et al. [48]	Seismic performance of precast industrial facilities following major earthquakes in the Italian territory	80
13	Pan et al. [49]	Strategies for integrating the use of off-site production technologies in house building	79
14	ČušBabič et al. [50]	Integrating resource production and construction using BIM	78
15	Yuan et al. [51]	A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste	76

frequency. According to Figure 8, a total of 29 documents received more than 20 co-citations. Among them, Magliulo et al. [44] (frequency = 50) reached the highest position, followed by Li et al. [7] (frequency = 38), Aye [38] (frequency = 36), Toniolo and Antonella [52] (frequency = 35), Bournas et al. [53] (frequency = 33), Mao et al. [42] (frequency = 31), Jaillon et al. [54] (frequency = 30), Belleri et al. [48] (frequency = 29), Pan et al. [49] (frequency = 27), Jaillon and Poon [55] (frequency = 24), Tam et al. [56] (frequency = 23), and others. There were no documents with high betweenness centralities.

In addition, as many as 41 documents obtained strong citation bursts, and the top 14 documents with strongest citation bursts in each corresponding period are shown in Table 10. It is worth noting that documents of Jaillon's research team obtained citation bursts three times from 2012

to 2017, indicating that their research findings have drawn high attentions in that time period. Furthermore, four documents obtained citation bursts from 2017 to 2019. The topics of the four documents were prefabricated houses in China, seismic performance, BIM application in prefabrication construction, and sustainable performance of different construction methods, respectively, which deserved more attentions.

2) *Co-Citation Clusters' Analysis*. Based on the keywords of the documents cited in each cluster, a total of 11 significant co-citation clusters were identified, as shown in Figure 8 (#0 to #10) and Table 11. The log likelihood ratio (LLR) method, which selected the best cluster labels based on uniqueness and coverage, was adopted to find the clusters. The yellow and pink color polygons shown in Figure 8 represent the



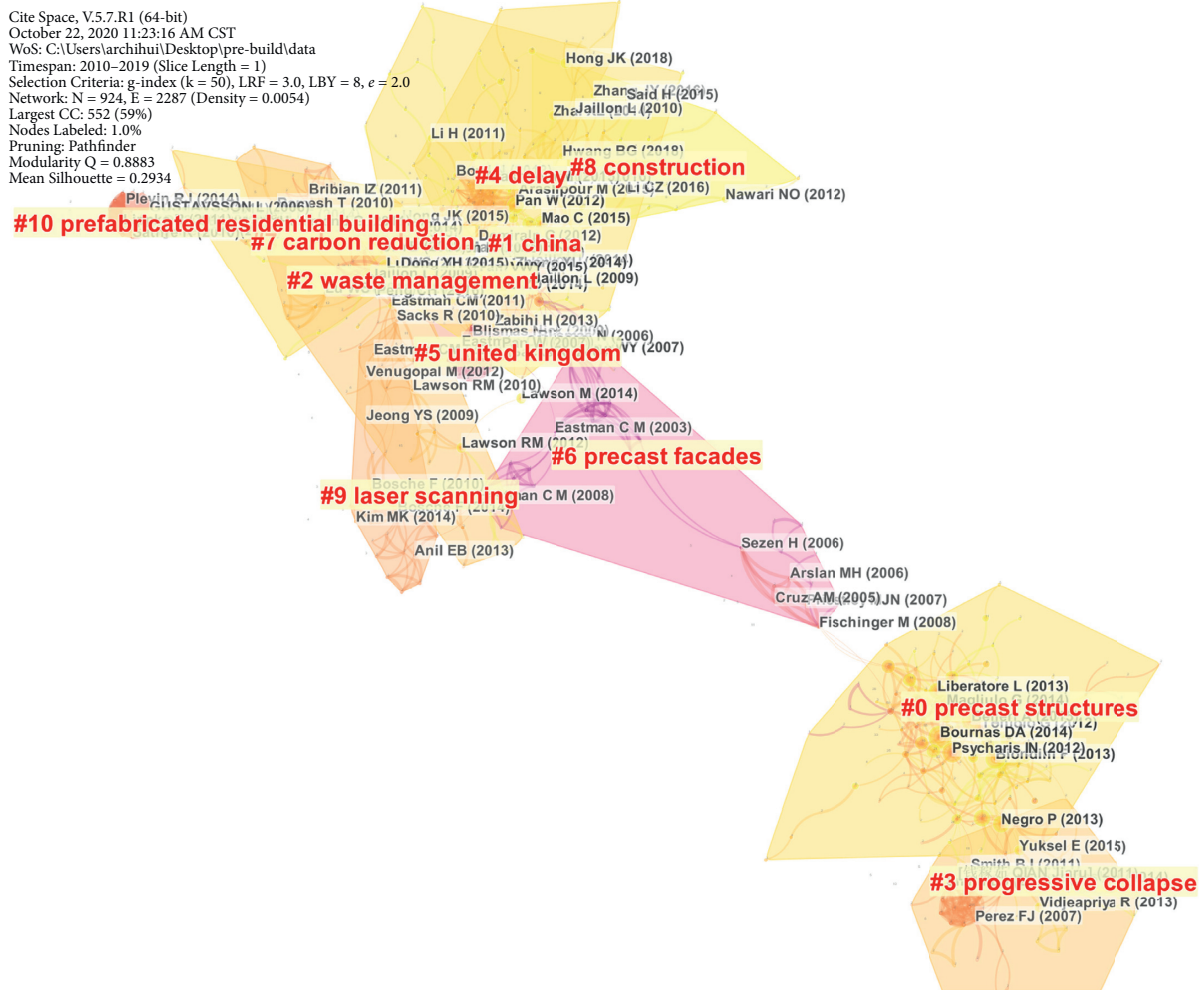


FIGURE 8: Document co-citation network.

TABLE 10: Top 14 documents co-citation with the strongest citation bursts in each corresponding period.

Document	Strength	Begin (year)	End (year)
R. Sacks et al. [57]	3.5128	2010	2012
Blismas et al. [58]	3.5892	2010	2014
Tam et al. [56]	8.9887	2010	2015
Fischinger et al. [59]	3.515	2010	2016
Magliulo et al. [44]	4.1727	2011	2016
Jaillon et al. [54]	7.1729	2012	2017
Perez et al. [60]	3.3533	2014	2015
Jaillon and Poon [61]	4.0479	2014	2016
Psycharis and Mouzakis [62]	4.1322	2014	2017
Jaillon and Poon [11]	4.308	2015	2017
Arif and Egbu [63]	3.7999	2017	2019
Babič and Dolšek [64]	3.9501	2017	2019
ČušBabič et al. [50]	2.9196	2017	2019
Chen et al. [37]	2.4062	2017	2019

coverages and sizes of the clusters. Among all the identified clusters, cluster #0 “precast structures” was the largest one with 111 members, and cluster #10 “prefabricated residential building” was the smallest one with 22 members. The silhouette metric represents the average homogeneity of each

cluster, and a higher silhouette score indicates a higher consistency of cluster members. All the clusters had silhouette scores greater than 0.8 (as shown in Table 11), suggesting that all these clusters had good consistency. For each cluster, the mean year (as shown in Table 11) indicates whether the documents of clusters are old or new. The mean year of cluster #6 was the oldest (2006), indicating that the documents of cluster #6 were older than others. Moreover, the representative document (as shown in Table 11) of each cluster was the highest co-citation document within the cluster. The details of the clusters are illustrated as follows.

Cluster #0 “precast structures” had 111 members. The representative document of this cluster was Bournas et al. [53]. This paper investigated the causes of structural damages to prefabricated industrial buildings after the earthquake in the Po Valley in the northern Italy region and proposed measures and opinions that could improve their seismic performance, such as applying simply supported beams and rational design of pinned beam-column connections to strengthen the existing precast buildings.

Cluster #1 “China” had 85 members. The representative document was Li et al. [7]. This document conducted a comprehensive study on the global assembly construction

TABLE 11: Co-citation clusters of prefabricated building research in 2011–2019.

Cluster ID	Size	Silhouette	Cluster label (LLR)	Alternative label	Mean year	Representative document
#0	111	0.984	Precast structures	Precast concrete structures; experimental testing	2013	Bournas et al. [53]
#1	85	0.825	China	Operational hedging; supply chain coordination	2013	Li et al. [7]
#2	59	0.922	Waste management	Building deconstruction; construction waste	2011	Lu and yuan [65]
#3	49	0.96	Progressive collapse	Column removal scenario; hybrid structures	2012	Smith et al. [66]
#4	42	0.982	Delay	Workflow variance; performance measures	2014	Chen et al. [37]
#5	32	0.973	United Kingdom	Construction management; off-site production	2009	Lawson et al. [67]
#6	32	0.965	Precast facades	Fabrication engineering; computer aided	2006	Blismas et al. [58]
#7	29	0.929	Carbon reduction	Life cycle assessment; low carbon building	2013	Ambrose and Leif [68]
#8	28	0.915	Construction	Prefabrication housing production; decision-making	2015	Li et al. [69]
#9	23	0.964	Laser scanning	Precast concrete elements; quality assessment	2011	Aye et al. [38]
#10	22	0.994	Prefabricated residential building	Composite beams; buildings' structures and design	2010	ACI Committee 318 [70]

management and systematically summarized the research and development of MPC. Li et al. [7] analyzed the major countries/regions and scientific research institutions in this field. This research also put forward the most popular research topics and the applications of some innovative technologies and provided recommendations for the future development directions of MPC research.

Cluster #2 “waste management” had 59 members and the representative document was Lu and Yuan [65]. In this paper, through the case analysis of three prefabricated component factories located in China’s Pearl River Delta Region (PRDR), the component prefabrication process and the sea transportation process were tracked and analyzed to explore the upstream process of offshore assembly buildings in Hong Kong.

Cluster #3 “progressive collapse” had 49 members. The representative document of this cluster by Smith et al. [66] discussed the lateral load behavior of two types of hybrid precast concrete shear wall test specimens and a third precast specimen’s behavior designed to emulate monolithic cast-in-place RC shear walls. The findings indicated the potential of using precast walls in seismic regions and revealed important detailing considerations.

Cluster #4 “delay” had 42 members, and the representative document of this cluster is Chen et al.’s study [37], which demonstrates the current U.S. industry emphasis on construction method selection and identifies seven dimensions of sustainable performance criteria assisting construction practitioners in selecting an appropriate construction method.

Cluster #5 “United Kingdom” had 32 members. The representative document of the cluster is Lawson et al. [67], which took three high-rise residential buildings with 12, 17, and 25 stories as cases to show how the modular structural systems’ actions affected the concept of architectural design. Based on the case studies, this article also gave an overview of

modular buildings with the sustainability benefits and economics.

Cluster #6 “precast facades” had 32 members and the representative document of this cluster was Blismas et al. [58]. This paper demonstrated that softer issues such as health, safety, and sustainability were some of the most significant benefits of off-site production. The decisions to select one construction method over another involving off-site production should be made based on its value, not just cost.

Cluster #7 “carbon reduction” had 29 members and the representative document was the study carried out by Ambrose and Leif [68]. They analyzed the primary energy use of conventional and passive buildings utilizing different heating systems and their carbon footprint in the whole life cycle. It was concluded that the selection of the end-use heating system was as important as the construction technologies of passive house. For example, it would be an effective means for a wooden house to use biomass-based cogenerated district heat to reduce primary energy use.

Cluster #8 “construction” had 28 members. The representative document was the study carried out by Li et al. [69]. This study analyzed the stakeholder-associated risk factors in prefabrication construction projects using the social network analysis. Building information modeling (BIM)-centered strategies were also proposed to facilitate and strengthen communication between shareholders to reduce the risk of poor communication and information error.

Cluster #9 “laser scanning” had 23 members and the representative document was Aye et al. [38]. This article took prefabricated multistory apartment buildings as an example, comparatively studied prefabricated steel structures, prefabricated wood structures, and traditional concrete buildings from the aspects of building production, construction methods, building service life, and reuse methods, and counted the hidden energy in its full life cycle. This article

provided a reference for construction sustainable development.

Cluster #10 “prefabricated residential building” had 22 members, among them; the most representative document was ACI Committee 318 [70], which was a standard of the American Concrete Institute. This standard covers the materials, design, and construction of structural concrete used in buildings which were applicable in nonbuilding structures and covers the strength evaluation of existing concrete structures.

## 4. Discussion

**4.1. Recommendation.** Although prefabricated buildings have been adopted in the past few decades, this technology has received much more attention in the last decade. In the past five years, the research on prefabricated buildings in developing countries has greatly increased based on the above analyses on countries and regions, research institutions, and contributions of scholars. We have observed a shift in the research focus as well in developing countries. For example, in China, there is still a great demand for construction. However, at the same time, China is facing environmental pollutions caused by construction works. Therefore, policy-oriented prefabricated buildings are promoted in various cities in China. Research on the construction technology of prefabricated buildings has received a lot of attention in the early years of the past decade, which is mostly in the engineering field. However, in the recent three to five years, research on prefabricated buildings has developed rapidly in the fields of environmental sustainability, green, and ecology, as sustainability has become one of the most important national development goals in China.

Productization of buildings has gradually become a major research direction. Especially in developing countries, industrialization of the construction sector has just started. At this moment, the production cost and construction cost of prefabricated buildings are relatively high. Therefore, more research studies on optimizing the industrial chain, saving labor and cost, and increasing the coupling rate of design and actual construction are needed to improve the economic benefits of prefabricated buildings. A few future research directions for prefabricated buildings can be foreseen, including

- (1) New technologies combined with prefabricated buildings, such as virtual design and construction (VDC) based on BIM, artificial intelligence (AI) technology, 3D scanning, and RFID, will receive more attention and research in the future. The implementation of new technologies will further improve the design, construction, and operation and maintenance of prefabricated buildings and further promote the adoption of prefabrication.
- (2) More types of prefabricated buildings should be paid attention to, not only reinforced concrete, steel structures, and wooden structures but also bamboo structures, membrane structures, etc., and more regionally related prefabricated building types can be

discussed. It is desired to have different types of prefabricated buildings according to the needs of different regions, considering various factors such as the economy, policy, environment, climate, and resources.

- (3) The cost optimization and carbon emissions of prefabricated buildings will become a difficulty that needs to be solved in the future. It is necessary to bridge this gap and establish a more reliable business model that can deliver prefabricated buildings with low construction cost and carbon emission.

**4.2. Limitations.** This paper used Citespace as a data analysis software to analyze the selected documents with the subjects, keywords, journals, authors, institutes, and citations. The information displayed is sufficient, while the expression and classification of figures need to be further improved with the update of this software. Correlation analysis software should be used to compare the differences in results produced by different software.

The focus and direction of the research can be linked to the timeline so as to directly observe the changes of research over time, discover the research rules in it, and grasp the updated research trends. The research hotspots in recent years should continue to be studied and highlighted in order to give researchers a clearer focus for future research on prefabricated buildings.

## 5. Conclusion

Prefabricated building has continued to attract scholars and practitioners all over the world in recent years. A scientometric review is applied to analyze the trends of global prefabricated buildings research in this study, which included co-author analysis, co-word analysis, and co-citation analysis.

The lead researchers on prefabricated building research were identified by the analysis of co-authorship and author co-citation. Bruno Dal Lago, Geoffrey Qiping Shen, and Giandomenico Toniolo were the most productive authors, and Jaillon Lara, Vivian W. Y. Tam, and M. J. N. Priestley got the top three most co-citations. Some authors without many publications and co-citations still received high citation bursts, such as T. Paulay, Giovanni Fabbrocino, R. M. Lawson, and Nenad Čuš Babič, which represented the importance of their research in specific time periods. The above scholars are mostly originated from China, the USA, and Italy. Furthermore, several research institutions such as Tongji University, Hong Kong Polytechnic University, and University of Hong Kong achieved the highest productivity in the field of prefabricated building research and Shenzhen University was the most active institution in the recent two years.

Engineering, civil engineering, construction, and building technology were the most important subject categories which received most publication records. Subject categories that got high citation bursts in the two years, including environmental studies, green and sustainable

science and technology, environmental science and ecology, and environmental science, were all related to environmental sustainability. In terms of the keywords, “precast concrete,” “timber structure,” “seismic,” “aggregate,” “algorithm,” “construction and demolition waste,” “composite,” “technology,” and “cladding panel” received high citation bursts, showing the diversity of research hotspots on prefabricated buildings.

Several journals such as *Engineering Structures*, *Automation in Construction*, *Journal of Cleaner Production*, *Energy and Buildings*, and *Construction and Building Materials* have published significant findings and also received high co-citation frequency in the last ten years, which indicates their continuous research impacts on prefabricated buildings. Chen et al. [35] got the most citations, which was published in *Automation in Construction*. According to the analysis of document co-citation, R. Sacks et al. [55] received the most co-citations, and Arif and Egbu [62], Babič and Dolšek [11], ČušBabič et al. [63], and Chen et al. [35] got high citation bursts over the past three years. Some of these publications were closely related to the BIM uses and sustainability of prefabricated buildings, implying that information technology and life cycle assessment were two critical research topics for prefabricated buildings in recent years. Moreover, 11 co-citation clusters were identified based on the analyzed documents’ keywords. Thus, some hot topics related to prefabricated building research were identified, including precast concrete structures, supply chain coordination, building deconstruction, construction waste, prefabricated housing production, computer aided, workflow variance, life cycle assessment, quality assessment, composite beams, hybrid structures, low carbon building, and off-site production.

In summary, this study conducted a comprehensive and scientific analysis of the global prefabricated building research from different perspectives. This study not only provides scholars with the development status and research hotspots of prefabricated building research but also provides key findings to facilitate the adoption and implementation of prefabricated buildings for practitioners and eventually promote the development of prefabricated building industry.

## Data Availability

No data were used to support this study.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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## References

- [1] N. Stern, “The economics of climate change: the stern review,” *Cabinet Office HM Treasury*, 2007.
- [2] S. Solomon, D. Qin, M. Manning et al., *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change IPCC Fourth Assessment Report (AR4)*, Cambridge University Press, Cambridge, England, 2007.
- [3] G. Sparkman, A. Gibb, and R. Neale, “Construction Industry Research and Information Association,” *Standardisation and preassembly: adding value to construction projects*, CIRIA report 176, 1999.
- [4] W. Nadim and J. S. Goulding, “Offsite production in the UK: the way forward? A UK construction industry perspective,” *Construction Innovation*, vol. 10, no. 2, pp. 181–202, 2010.
- [5] Y.-H. Chiang, E. H.-W. Chan, and K.-L. Lawrence, “Prefabrication and barriers to entry—a case study of public housing and institutional buildings in Hong Kong,” *Habitat International*, vol. 30, pp. 482–499, 2006.
- [6] A. Baldwin, C.-S. Poon, L.-Y. Shen, S. Austin, and I. Wong, “Designing out waste in high-rise residential buildings: analysis of precasting methods and traditional construction,” *Renewable Energy*, vol. 34, no. 9, pp. 2067–2073, 2009.
- [7] Z. Li, G. Q. Shen, and X. Xue, “Critical review of the research on the management of prefabricated construction,” *Habitat International*, vol. 43, pp. 240–249, 2014.
- [8] Z. Wang, H. Hu, J. Gong, X. Ma, and W. Xiong, “Precast supply chain management in off-site construction: a critical literature review,” *Journal of Cleaner Production*, vol. 232, pp. 1204–1217, 2019.
- [9] I. Y. Wuni and G. Q. Shen, “Barriers to the adoption of modular integrated construction: systematic review and meta-analysis, integrated conceptual framework, and strategies,” *Journal of Cleaner Production*, vol. 249, Article ID 119347, 2020.
- [10] S. Navaratnam, T. Ngo, T. Gunawardena, and D. Henderson, “Performance review of prefabricated building systems and future research in Australia,” *Buildings*, vol. 9, no. 2, p. 38, 2019.
- [11] L. Jaillon and C. S. Poon, “The evolution of prefabricated residential building systems in Hong Kong: a review of the public and the private sector,” *Automation in Construction*, vol. 18, no. 3, pp. 239–248, 2009.
- [12] C. Newton, S. Backhouse, A. Aibinu et al., “Plug n play: future prefab for smart green schools,” *Buildings*, vol. 8, no. 7, p. 88, 2018.
- [13] A. Bukauskas, P. Mayencourt, P. Shepherd et al., “Whole timber construction: a state of the art review,” *Construction and Building Materials*, vol. 213, pp. 748–769, 2019.
- [14] M. Kamali and K. Hewage, “Life cycle performance of modular buildings: a critical review,” *Renewable and Sustainable Energy Reviews*, vol. 62, pp. 1171–1183, 2016.
- [15] F. E. Boafo, J.-H. Kim, and J.-T. Kim, “Performance of modular prefabricated architecture: case study-based review and future pathways,” *Sustainability*, vol. 8, no. 6, p. 558, 2016.
- [16] Y. C. Kurama, S. Sriharan, R. B. Fleischman et al., “Seismic-resistant precast concrete structures: state of the art,” *Journal of Structural Engineering*, vol. 144, no. 4, Article ID 03118001, 2018.
- [17] R. Jin, J. Hong, and J. Zuo, “Environmental performance of off-site constructed facilities: a critical review,” *Energy and Buildings*, vol. 207, Article ID 109567, 2020.



- [18] X. Xu, J. Yu, S. Wang, and J. Wang, "Research and application of active hollow core slabs in building systems for utilizing low energy sources," *Applied Energy*, vol. 116, pp. 424–435, 2014.
- [19] R. O'Hegarty and K. Oliver, "Review of precast concrete sandwich panels and their innovations," *Construction and Building Materials*, vol. 233, Article ID 117145, 2020.
- [20] P. Vähä, T. Heikkilä, P. Kilpeläinen, M. Järviluoma, and E. Gambao, "Extending automation of building construction - survey on potential sensor technologies and robotic applications," *Automation in Construction*, vol. 36, pp. 168–178, 2013.
- [21] M. R. Hosseini, I. Martek, E. K. Zavadskas et al., "Critical evaluation of off-site construction research: a Scientometric analysis," *Automation in Construction*, vol. 87, pp. 235–247, 2018.
- [22] R. Jin, S. Gao, A. Cheshmehzangi, and E. Aboagye-Nimo, "A holistic review of off-site construction literature published between 2008 and 2018," *Journal of Cleaner Production*, vol. 202, pp. 1202–1219, 2018.
- [23] D. J. Hess, *Science Studies: An Advanced Introduction*, New York University Press, New York, NY, 1997.
- [24] L. Leydesdorff and S. Milojević, "Scientometrics," *International Encyclopedia of the Social & Behavioral Sciences*, vol. 8, no. 5, pp. 322–327, 2015.
- [25] C. Chen, "Science mapping: a systematic review of the literature," *Journal of Data and Information Science*, vol. 2, no. 2, pp. 1–40, 2017.
- [26] W. W. Hood and C. S. Wilson, "The literature of bibliometrics, scientometrics, and informetrics," *Scientometrics*, vol. 52, no. 2, pp. 291–314, 2001.
- [27] A. Pouris and A. Pouris, "Scientometrics of a pandemic: HIV/AIDS research in South Africa and the world," *Scientometrics*, vol. 86, no. 2, pp. 541–552, 2011.
- [28] Yi Wen, P. Albert, and C. Chan, "Critical review of labor productivity research in construction journals," *Journal of Management in Engineering*, vol. 30, no. 2, pp. 214–225, 2013.
- [29] L. Butler and M. S. Visser, "Extending citation analysis to non-source items," *Scientometrics*, vol. 66, no. 2, pp. 327–343, 2006.
- [30] C. Chen, *CiteSpace: A Practical Guide for Mapping Scientific Literature*, Nova Science Publishers, New York, USA, 2016.
- [31] C. Chen: The CiteSpace Manual. 2014, <http://cluster.ischool.drexel.edu/~cchen/citespace/CiteSpaceManual.pdf>.
- [32] L. C. Freeman, "A set of measures of centrality based on betweenness," *Sociometry*, vol. 40, no. 1, pp. 35–41, 1977.
- [33] Y. Gao and X.-L. Tian, "Prefabrication policies and the performance of construction industry in China," *Journal of Cleaner Production*, vol. 253, Article ID 120042, 2020.
- [34] J. Li, H. Liu, J. Zuo, R. Xia, and G. Zillante, "Are construction enterprises ready for industrialized residential building policy? A case study in Shenzhen," *Sustainable Cities and Society*, vol. 41, pp. 899–906, 2018.
- [35] G. Liu, J. H. Nzige, J. H. Nzige, and K. Li, "Trending topics and themes in offsite construction (OSC) research," *Construction Innovation*, vol. 19, no. 3, pp. 343–366, 2019.
- [36] H. Small, "Co-citation in the scientific literature: a new measure of the relationship between two documents," *Journal of the American Society for Information Science*, vol. 24, no. 4, pp. 265–269, 1973.
- [37] Y. Chen, G. E. Okudan, and D. R. Riley, "Sustainable performance criteria for construction method selection in concrete buildings," *Automation in Construction*, vol. 19, no. 2, pp. 235–244, 2010.
- [38] A. Lu, T. Ngo, R. H. Crawford et al., "Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules," *Energy and Buildings*, vol. 47, pp. 159–168, 2012.
- [39] M. Pavlović, Z. Markovic, M. Veljkovic et al., "Bolted shear connectors vs. headed studs behaviour in push-out tests," *Journal of Constructional Steel Research*, vol. 88, pp. 134–149, 2013.
- [40] L. B. Firth, R. C. Thompson, K. K. Bohn et al., "Between a rock and a hard place: environmental and engineering considerations when designing coastal defence structures," *Coastal Engineering*, vol. 87, pp. 122–135, 2014.
- [41] C. Mao, Q. Shen, L. Shen, and L. Tang, "Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: two case studies of residential projects," *Energy and Buildings*, vol. 66, pp. 165–176, 2013.
- [42] B. Mas, A. Cladera, T. d. Olmo, and F. Pitarch, "Influence of the amount of mixed recycled aggregates on the properties of concrete for non-structural use," *Construction and Building Materials*, vol. 27, no. 1, pp. 612–622, 2012.
- [43] C. M. Eastman, Y.-S. Jeong, R. Sacks, and I. Kaner, "Exchange model and exchange object concepts for implementation of national BIM standards," *Journal of Computing in Civil Engineering*, vol. 24, no. 1, pp. 25–34, 2010.
- [44] G. Magliulo, M. Ercolino, C. Petrone, O. Coppola, and G. Manfredi, "The emilia earthquake: seismic performance of precast reinforced concrete buildings," *Earthquake Spectra*, vol. 30, no. 2, pp. 891–912, 2014.
- [45] W. Lu and H. Yuan, "Exploring critical success factors for waste management in construction projects of China," *Resources, Conservation and Recycling*, vol. 55, no. 2, pp. 201–208, 2010.
- [46] Y. Chen, A. K. Athienitis, and K. Galal, "Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 1, BIPV/T system and house energy concept," *Solar Energy*, vol. 84, no. 11, pp. 1892–1907, 2010.
- [47] Z. Qu, A. Wada, S. Motoyui, H. Sakata, and S. Kishiki, "Pin-supported walls for enhancing the seismic performance of building structures," *Earthquake Engineering & Structural Dynamics*, vol. 41, no. 14, pp. 2075–2091, 2012.
- [48] A. Belleri, E. Brunesi, R. Nascimbene, M. Pagani, and P. Riva, "Seismic performance of precast industrial facilities following major earthquakes in the Italian territory," *Journal of Performance of Constructed Facilities*, vol. 29, no. 5, Article ID 04014135, 2015.
- [49] W. Pan, A. G. F. Gibb, A. R. J. Dainty, and A. R. J. Dainty, "Strategies for integrating the use of off-site production technologies in house building," *Journal of Construction Engineering and Management*, vol. 138, no. 11, pp. 1331–1340, 2012.
- [50] N. ČušBabič, P. Peter, and D. Rebolj, "Integrating resource production and construction using BIM," *Automation in Construction*, vol. 19, no. 5, pp. 539–543, 2010.
- [51] H. Yuan, A. R. Chini, Y. Lu, and L. Shen, "A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste," *Waste Management*, vol. 32, no. 3, pp. 521–531, 2012.
- [52] G. Toniolo and A. Colombo, "Precast concrete structures: the lessons learned from the L'Aquila earthquake," *Structural Concrete*, vol. 13, no. 2, pp. 73–83, 2012.
- [53] D. A. Bournas, P. Negro, and F. F. Taucer, "Performance of industrial buildings during the Emilia earthquakes in

- Northern Italy and recommendations for their strengthening," *Bulletin of Earthquake Engineering*, vol. 12, no. 5, pp. 2383–2404, 2013.
- [54] L. Jaillon, C. S. Poon, and Y. H. Chiang, "Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong," *Waste Management*, vol. 29, no. 1, pp. 309–320, 2009.
- [55] L. Jaillon and C. S. Poon, "Life cycle design and prefabrication in buildings: a review and case studies in Hong Kong," *Automation in Construction*, vol. 39, no. 1, pp. 195–202, 2014.
- [56] W. Y. T. Vivian, W. H. F. Ivan, C. P. S. Michael, and O. O. Stephen, "Best practice of prefabrication implementation in the Hong Kong public and private sectors," *Journal of Cleaner Production*, vol. 109, no. 16, pp. 216–231, 2015.
- [57] R. Sacks, C. M. Eastman, and G. Lee, "Process model perspectives on management and engineering procedures in the precast/prestressed concrete industry," *Journal of Construction Engineering and Management*, vol. 130, no. 2, pp. 206–215, 2004.
- [58] N. Blismas, C. Pasquire, and A. Gibb, "Benefit evaluation for off-site production in construction," *Construction Management and Economics*, vol. 24, no. 2, pp. 121–130, 2006.
- [59] M. Fischinger, M. Kramar, and T. Isaković, "Cyclic response of slender RC columns typical of precast industrial buildings," *Bulletin of Earthquake Engineering*, vol. 6, no. 3, pp. 519–534, 2008.
- [60] F. J. Perez, R. Sause, and S. Pessiki, "Analytical and experimental lateral load behavior of unbonded posttensioned precast concrete walls," *Journal of Structural Engineering*, vol. 133, no. 11, pp. 1531–1540, 2007.
- [61] L. Jaillon and C. S. Poon, "Sustainable construction aspects of using prefabrication in dense urban environment: a Hong Kong case study," *Construction Management and Economics*, vol. 26, no. 9, pp. 953–966, 2008.
- [62] I. N. Psycharis and H. P. Mouzakis, "Shear resistance of pinned connections of precast members to monotonic and cyclic loading," *Engineering Structures*, vol. 41, pp. 413–427, 2012.
- [63] M. Arif and C. Egbu, "Making a case for offsite construction in China," *Engineering, Construction and Architectural Management*, vol. 17, no. 6, pp. 536–548, 2010.
- [64] A. Babič and M. Dolšek, "Seismic fragility functions of industrial precast building classes," *Engineering Structures*, vol. 118, no. 1, pp. 357–370, 2016.
- [65] W. Lu and H. Yuan, "Investigating waste reduction potential in the upstream processes of offshore prefabrication construction," *Renewable and Sustainable Energy Reviews*, vol. 28, pp. 804–811, 2013.
- [66] B. J. Smith, Y. C. Kurama, and M. J. McGinnis, "Behavior of precast concrete shear walls for seismic regions: comparison of hybrid and emulative specimens," *Journal of Structural Engineering*, vol. 139, no. 11, pp. 1917–1927, 2013.
- [67] R. Mark Lawson, R. G. Ogden, and R. Bergin, "Application of modular construction in high-rise buildings," *Journal of Architectural Engineering*, vol. 18, no. 2, 2012.
- [68] D. Ambrose and L. Gustavsson, "Life cycle primary energy use and carbon footprint of wood-frame conventional and passive houses with biomass-based energy supply," *Applied Energy*, vol. 112, pp. 834–842, 2013.
- [69] C. Z. Li, J. Hong, F. Xue, G. Q. Shen, X. Xu, and M. K. Mok, "Schedule risks in prefabrication housing production in Hong Kong: a social network analysis," *Journal of Cleaner Production*, vol. 134, pp. 482–494, 2016.
- [70] ACI Committee 318, *Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary*, p. 473, American Concrete Institute, Michigan, USA, 2007.