Article

Prefabricated Construction Risks: A Holistic Exploration through Advanced Bibliometric Tool and Content Analysis

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Abstract: Prefabricated construction (PC) offers advantages to the architecture, engineering, and construction (AEC) industry such as quality production, fast project completion, low waste output, high environmental sensitivity, and high security. Although PC has several advantages, knowledge gaps persist, necessitating a comprehensive bibliometric study. This research adopts a holistic bibliometric approach, combining qualitative (systematic literature review) and quantitative (bibliometric analysis) methods to assess the current state of prefabricated construction risks (PCRs) research and identify the literature trends. Unlike previous PCRs studies, our research capitalizes on the quantitative analysis capabilities of the Bibliometrix R-tool. We introduce innovative measures, such as the *h*-index, thematic mapping, and trend topic analysis, to deepen the understanding of the PCRs research landscape. Moreover, this study explores the intellectual structure of PCR research through keyword analysis, cluster analysis, and thematic evaluation, providing valuable insights into scientific studies, collaborations, and knowledge dissemination. In our study, following a systematic literature review to understand the existing knowledge, the R-studio Bibliometrix package is used to map the field, identify gaps in the field, and analyze the trends. This study involves a comprehensive bibliometric analysis of 150 articles in the field of PCRs, with data obtained from the Web of Science spanning from 2000 to 2023. The findings from the analyses reveal that the studies were divided into four different clusters: management, programming, logistics, and supply chain. Additionally, themes such as the integration of PC with Building Information Management (BIM), barriers, and stakeholders were also explored. The analyses indicate a growing awareness of PCRs, particularly in specific areas such as management, performance, and supply chain. This study stands out for its unique methods, analytical approach, and the use of specialized software. It provides valuable insights and suggestions for future studies.

Keywords: prefabricated construction risks; bibliometric analysis; R-package

1. Introduction

Prefabricated construction (PC) is an efficient construction method in which prefabricated components can be manufactured in a controlled environment and quickly assembled on-site [1]. In comparison to traditional construction methods in architecture, engineering, and construction (AEC) industry, PC has several benefits that include fast project completion, improved quality and strength [2–4], less material waste [5,6], higher seismic load resistance [7], sustainability promotion and clean production [8–10], low environmental impacts [11], and safer working environment [12]. Researchers from developed countries, including the USA, the UK, Hong Kong, Sweden, and Australia, have provided significant contributions to the development of the prefabrication domain, while those from developing countries, including China, Turkey, and Israel where construction remains the main economic activity, have shown an increasing interest in promoting prefabrication-related research [13]. Although PC has several advantages and benefits, some challenges hinder

their widespread adoption. By addressing risks and finding innovative solutions, PC can evolve into a mainstream construction approach, revolutionizing the AEC industry.

1.1. Existing Studies on PC

Scholars from around the world have identified and addressed the challenges associated with PC, endeavoring to enhance its implementation in the AEC industry. Their collective efforts have focused on resolving a wide range of challenges, including health and safety problems [12,14–22]; supply chain and supply chain resilience problems [5,23–31]; logistical problems [32,33]; schedule and delay problems [34–39]; information technology problems [40]; modular elements' tolerance problems [41,42]; problems related with crane operations [43]; problems related with policy drivers [30]; design problems [44,45]; quality problems [46]; and investment and cost problems [10,47–52].

Though previous studies are noteworthy and influential, they tend to be primarily focused on either quantitative or qualitative analyses, relying solely on specific methodologies such as online surveying, case studies, semi-structured interviews, or system dynamics. However, it is important for users to be aware of all the risks while selecting PC systems. Therefore, review studies are becoming increasingly significant to acquire an overview of all prefabricated construction risks (PCRs). The acquisition of a comprehensive understanding of the PC research field necessitates scholars to investigate it from diverse perspectives, leveraging prior studies and expanding the existing body of knowledge. This is vital for an accurate portrayal of the research field, to enhance scholars' comprehension of the current state and future trends in PC-related topics, and to enable them to focus their studies more effectively. Pickering and Byrne [53] assert that an essential initial step for researchers when starting a new topic is to perform a literature search. In this regard, systematic literature reviews and bibliometric analyses play a pivotal role in offering invaluable guidance to the new researchers. According to Grant and Booth [54], systematically synthesized summaries are necessary for researchers to make informed decisions when conducting research on various topics. As a result, systematic analyses are used to reduce information pollution and concisely synthesize the most relevant studies. In the context of gaining deeper insights into the field of PCR, previous review studies have endeavored to analyze the prior research works. These studies can be categorized into two groups: quantitative and qualitative review studies.

A short brief of the aforementioned PCRs review studies, given in Table 1, sheds light on their contributions. While qualitative PCRs review studies (ID: 1–6 in Table 1) offer valuable insights into PCRs, their analysis primarily relies on subjective and qualitative analyses and are limited to specific areas (e.g., construction engineering and management, and health and safety), which are insufficient for precisely and holistically representing the in-depth knowledge structure of PCR studies. Notably, Wuni et al. [55] reviewed 39 empirical studies systematically, identifying major risks affecting PC development in qualitative studies. Wuni and Shen [56] made significant contributions to the field through qualitative review methods, addressing notable research topics in PCRs. Fagbenro et al. [57] performed systematic literature review to identify the influence of PC on mental health of workers. Li et al. [58] highlighted the barriers to development of PC in China using the news analysis method. While qualitative analysis in these reviews facilitates in-depth discussions, it should be acknowledged that it may amplify the influence of the scholars' subjectivity.

In contrast, the quantitative literature reviews (ID: 7–12 in Table 1) provide a wide range of perspectives on the PCR domain through objective analyses. In recent years, researchers have used quantitative instruments such as meta-analysis and bibliometric analysis to enhance previous qualitative reviews of PCRs studies. For example, Li et al. [59] conducted a bibliometric method to publish PCRs research from a risk management perspective. Wuni et al. [60] analyzed 54 studies in PCRs research domain and determined PC risks across six dimensions. Li et al. [61] conducted a bibliometric and scientometric analysis of 376 prefabricated construction-related articles published between 2011 and 2021. Han et al. [62] performed a bibliometric review of PC supply chain management

research from 2000 to 2022 using VosWiever software, and identified the current research progress, trend, and future directions. Similarly, Liu et at. [63] overviewed 152 PC supply chain management articles from 2001 to 2018 through bibliometric and thematic analysis. Liu et al. [64] carried out a bibliometric analysis and cluster analysis to highlight PCRs related to quality control using VosViewer, focusing on PC-related publications from the past 20 years, and identified research gaps and future directions.

All of the aforementioned qualitative and quantitative works have made significant contributions to advancing our understanding of the PCRs research field. However, it is important to note that despite these contributions, there are still numerous aspects within this domain that require further investigation.

In order to fill the existing research gap in the literature on PCRs, it is essential to conduct a comprehensive and multidisciplinary bibliometric study aiming to collect a wider range of information, thereby providing a deeper understanding of the subject. This study seeks to continue the bibliometric journey, adopting a more holistic approach as a valuable complement to the previous bibliometric investigations. It is worth mentioning that most of previous PC-related studies have mainly focused on single-case analyses or specific countries (e.g., Canada, The United Kingdom, China, The USA, Australia, and Malaysia), which limits the ability to fully comprehend the entirety of risks associated with PC systems.

1.2. Contributions

To fill the research gap identified in the existing literature, this study undertakes a broad metrological and content analysis of PCRs domain within an intellectual structure. This study differs from prior bibliometric studies on PCRs in three ways.

First, this study employs a new bibliometric analysis platform named as Bibliometrix R software, which is designed for R language in 2017 and offers a set of tools for quantitative bibliometric analysis [65]. This new tool is adaptable and incorporates a number of additional statistical and graphical software. Using the R language to conduct a bibliometric analysis is a novel approach that enables an in-depth understanding of the PCRs research field.

Second, this study employs a diverse range of indices and metrological analysis methods to provide a comprehensive overview of the PCRs domain. Though certain types of indices and analyses, such as annual scientific production, active countries analysis, and journal source analysis, have been utilized in previous PCRs bibliometric studies, this study introduces a novel set of measures (e.g., *h*-index, keywords chronological change tendency analysis, thematic mapping, cluster analysis, thematic evaluation, trend topic analysis, and the year of first publication of authors). These innovative measures are being employed for the first time in PCRs bibliometric analyses, contributing to a more comprehensive understanding of the research landscape in this field.

Table 1. A brief summary of previous PC review studies.

ID	Study	Size	Period	Source	Type of Research	Main Method	Main Focus	Software Tool	Primary Discipline Focused	Type of Literature Review
1	Wuni et al. [55]	39 articles	1995–2019	Scopus	No bibliometric	Systematic literature review	Critical risk factors in the application of PC	-	Construction engineering and management	Qualitative
2	Wuni and Shen [56]	46 articles	2000–2019	Scopus	No bibliometric	Systematic literature review and meta-analysis	Barriers to the adoption of PC	-	Construction engineering and management	Qualitative
3	Fagbenro et al. [57]	75 articles	2000–2022	Scopus, Web of Science PubMed	No bibliometric	PRISMA systematic review	Influence of Prefabricated Construction on the Mental Health of Workers	-	Health and safety	Qualitative
4	Li et al. [58]	119 news report	2019	China National Knowledge Infrastructure	No bibliometric	Term Frequency-Inverse Document Frequency (TF-IDF) and content analysis	Barriers to the development of prefabricated buildings	-	Construction engineering and management	Qualitative
5	Wuni and Shen [9]	32 articles		Scopus Web of Science Taylor & Francis Emerald Google Scholar	No bibliometric	Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and Total Interpretive Structural Modelling (TISM)	Drivers of PC	-	Construction engineering and management	Qualitative
6	Li et al. [13]	66 articles	2000–2013	Scopus	No bibliometric	Score matrix	Reviewing management of PC	-	Construction engineering and management	Qualitative
7	Li et al. [7]	144 articles	1993–2022	Scopus	Bibliometric analysis	Scientific visualization [a]	Risk management in PC	VOSviewer	Construction engineering and management	Quantitative

Table 1. *Cont.*

ID	Study	Size	Period	Source	Type of Research	Main Method	Main Focus	Software Tool	Primary Discipline Focused	Type of Literature Review
8	Wuni et al. [60]	54 articles	1992–2020	Scopus	No bibliometric	Systematic literature review, Meta-synthesis and content analysis	Risks of PC	Excel	Construction engineering and management	Quantitative
9	Li et al. [61]	376 articles	2011–2021	Scopus Web of Science	Bibliometric analysis	Scientific visualization [b]	Management of PC	VOSviewer	Construction engineering and management	Quantitative
10	Han et al. [62]	131 articles	2011–2022	Web of Science	Bibliometric analysis	Scientific visualization [c]	Supply chain management in PC	VOSviewer	Construction engineering and management	Quantitative
11	Liu et al. [63]	152 articles	2001–2018	Elsevier, Web of Science, Emerald, and EBSCO Host	Bibliometric analysis	Scientific visualization [a]	Supply chain management in PC	VOSviewer	Construction engineering and management	Quantitative
12	Liu et al. [64]	42 articles	2000–2020	Web of Science	Bibliometric analysis and Content analysis	Scientific visualization [d]	Quality control for PC	VOSviewer	Construction engineering and management	Quantitative

[a] Journal citation analysis, document co-citation analysis, keyword co-occurrence analysis. [b] Country analysis, journal source analysis, keyword analysis. [c] Journal citation analysis, document co-citation analysis, keyword co-occurrence analysis, active country analysis. [d] journal citation analysis, document co-citation analysis, keyword co-occurrence analysis, overlay visualization.

Finally, the current study explores the intellectual structure of PCR research field by applying keyword analysis, cluster analysis, thematic evaluation, and trend topic analysis. The term "intellectual structure" refers to the organization and interrelation of knowledge within a specific research field or domain. Hossaini et al.'s [66] examination of intellectual structure provides a comprehensive perspective of scientific studies, research networks, and knowledge development in the subject [67]. These insights contribute to a better understanding of advancements, collaborations, and knowledge dissemination. Although previous bibliometric studies on PCRs have often used keywords and citation analyses, to the best of our knowledge, the current study is the first one to approach PCRs with an intellectual structure. To illustrate the intellectual structure of the PCRs research field from various perspectives, diverse science maps such as change in top 10 keywords by frequency, conceptual structure map, keywords co-occurrence network with time information, strategic diagrams, Sankey diagram, and cluster analysis are conducted. The science maps in this research differ from previous PCRs bibliometric studies in that they provide a global perspective and highlight notable characteristics of the PCRs research field. This study incorporates and extends the bibliometric findings of former PCRs literature analyses while also serving as a new reference for future bibliometric analysis in other research domains, utilizing the three mentioned approaches.

2. Research Methodology

This study adopted a holistic and broad bibliometric approach, exploring the field of PCRs by combining metrological analysis with content analysis. The bibliometric approach, which is extensively regarded as more reliable and impartial compared to alternative techniques [61], can provide important understanding into the features and structure of a certain domain in a systematic, transparent, and reproducible procedure [64,65]. This study uses a methodology similar to that of Pollack and Adler's [68] study which examines trends in project management in a broad context. Marovic et al. [69] used bibliometric mapping to evaluate performance management of civil engineers. Unlike these studies, detailed author analyses, cluster analyses and thematic evaluation analyses specific to PCRs were conducted in this study. Our methodology follows an inductive approach, starting with a detailed analysis of diverse datasets to derive specific findings. Subsequently, we discern patterns and themes from the identified results. Figure 1 presents a framework of the research methodology.

The research methodology encompasses two primary components: data preparation and a quantitative mixed review method. The first component involves the extraction and evolution of Bibliometrics Data, ensuring the data is appropriately collected and prepared for analysis. The second component employs a rigorous mixed review method, integrating both metrological analysis and content analysis. This approach is illustrated in Figure 1, highlighting the systematic flow and interrelationship of the methodology.

During the data preparation phase, a systematic approach is followed. Firstly, a suitable database is selected, and based on specific keywords and inclusion/exclusion criteria, relevant articles are retrieved from the chosen database. Following that, the retrieved articles are thoroughly screened and evaluated. In Section 2.1 and its corresponding subsections, comprehensive descriptions of the data preparation processes for bibliometric analyses are provided. These descriptions outline the systematic steps taken to ensure the data are appropriately collected, organized, and prepared for subsequent analyses.

The second component of the methodology incorporates a rigorous mixed review method, integrating both metrological analysis and content analysis. To gather the required data for these analyses, this study utilizes the powerful Bibliometrix R package within the R Studio program. This package enables the collection and processing of data required for conducting various bibliometric analyses. Under the heading of "Metrological analysis", this study offers an overview and evaluation of PCRs by examining publications, journals, researchers, institutions, and countries in the PCRs field using a range of indices. On the other hand, "Content Analysis" is performed to explore the intellectual structure of

the PCRs field. Examining the intellectual structure in the PCRs literature is essential for providing a comprehensive overview of scientific advancements. The intellectual structure provides a holistic perspective on scientific studies, research networks, and knowledge generation within the field during bibliometric analysis. These analyses aid in understanding developments within the field, identifying collaborations, and tracking the dissemination of scientific knowledge. Additionally, intellectual structure analysis assists in identifying emerging discoveries, research trends, and in understanding collaborations and knowledge flow within the field. Briefly, the content analysis encompasses keyword analysis and trending topic analysis. The keyword analysis consists of frequently used keywords, keywords mapping analysis, temporal trends of keywords, thematic network analysis, cluster analysis and thematic evaluation analysis. The mixed review method including "Metrological analysis" and "Content Analysis" is subsequently conducted and evaluated in Section 3.
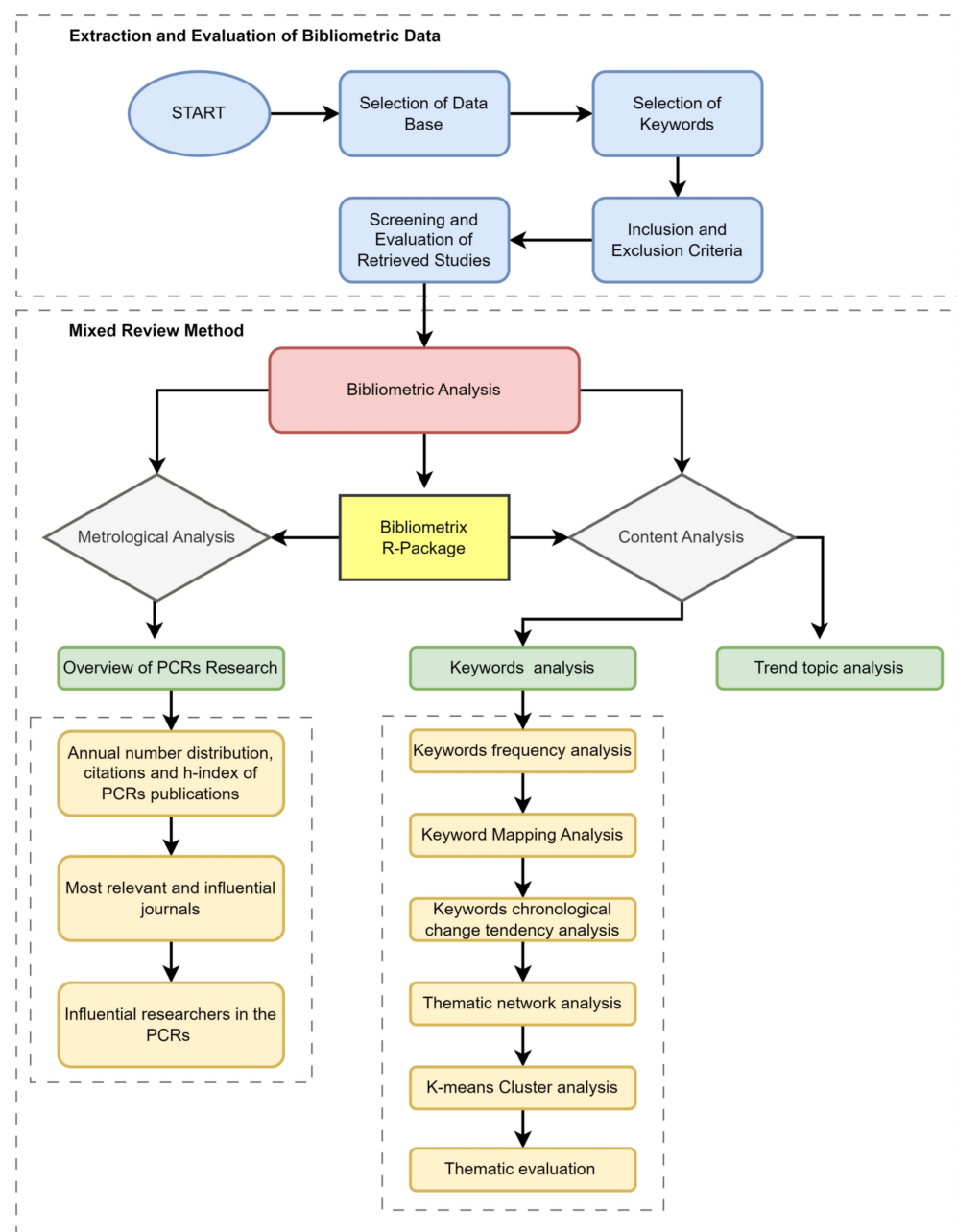

Figure 1. Framework of methodology.

2.1. Extraction of Bibliometric Data

The methodology of this study begins by obtaining relevant research data related to PCRs. Keywords and search databases used to uncover relevant studies are determined in this section. This section also contains the inclusion and exclusion criteria used to filter the retrieved studies. Finally, a uniform review procedure for screening the retrieved studies is described.

2.1.1. Database–Keyword Selection and Retrieving Articles

The extraction of bibliometric data commenced with the search process, aiming to identify databases that would provide a comprehensive coverage of the relevant studies, rather than limiting to specific journals. For this purpose, Web of Science (WoS) is selected to investigate the research domain. WoS is considered the gold standard database for bibliometric analysis [41]. In addition, WoS incorporates practically all key publications and built-in analytic proficiencies for constructing representative numbers [70]. Moreover, WoS utilizes superior citation-matching algorithms compared to Scopus [71], making it a valuable data source for our study.

After selecting the database, we identify and utilize the relevant keywords to effectively scan the database and retrieve the publications directly aligned with the scope of our study. To accomplish this, we identify and utilize relevant keywords closely related to prefabricated construction, such as "prefabricated building", "prefabricated construction", "precast concrete", "precast fabrication", "off-site construction", "off-site manufacture", "off-site production", and "modular construction". Additionally, we include keywords associated with risks, such as "barriers", "challenges", "hindrances", "problems", and "obstacles". We have intentionally excluded the keywords "highway" and "infrastructure" from the search to solely focus our study on superstructures. A scan has been carried out based on the search string below.

- All fields = "prefabricated building" OR "prefabricated construction" OR "precast concrete" OR "precast fabrication" OR "off*site construction" OR "off-site manufacture" OR "off-site production" OR "modular construction" AND "barriers" AND "challenges" AND "hindrances" AND "problems" AND "obstacles" AND "risks" NOT "highway" NOT "infrastructure".

The character "*" denotes a fuzzy search to capture relevant variations of a term.

2.1.2. Inclusion and Exclusion Criteria

In systematic literature review (SLR), determining inclusion and exclusion criteria is a significant step in filtering the retrieved research publications and keeping just the relevant ones. In addition, the inclusion and exclusion criteria establish the standards used in an SLR for categorizing the sample size from the universe of articles in search queries [72]. As a result, specific inclusion and exclusion criteria are set up for this study to analyze the obtained published literature. Our inclusion criteria consist of the following: (1) research which specifically focuses on PC within construction projects; (2) studies that delve into PC risks and (3) studies published in peer-review journals. Adopting a selective approach to academic journals in the research topic represents an efficient strategy for reducing the volume of the literature while upholding search quality [64]. To ensure rigorousness, conference papers were excluded due to widespread criticism concerning their lack of thorough peer-review procedures [60]. Finally, the exclusion criteria are identified as the following: (1) research published in languages other than English language; (2) articles which studied risks without considering PC aspects; and (3) studies without available full text.

2.1.3. Screening and Evaluation of Obtained Studies

Articles were selected on basis of metadata (ALL FIELDS) screening and full-text evaluations. Because this study aimed to analyze the most recent themes and trends in PC risks, the document type was determined to be an article or review, and the publishing

period was confined to the last 24 years (from 2000 to 2023). As of April 2023, 1771 articles were retrieved from WoS database. Then, the authors followed the SLR protocol for evaluating the obtained studies, as shown in Figure 2.
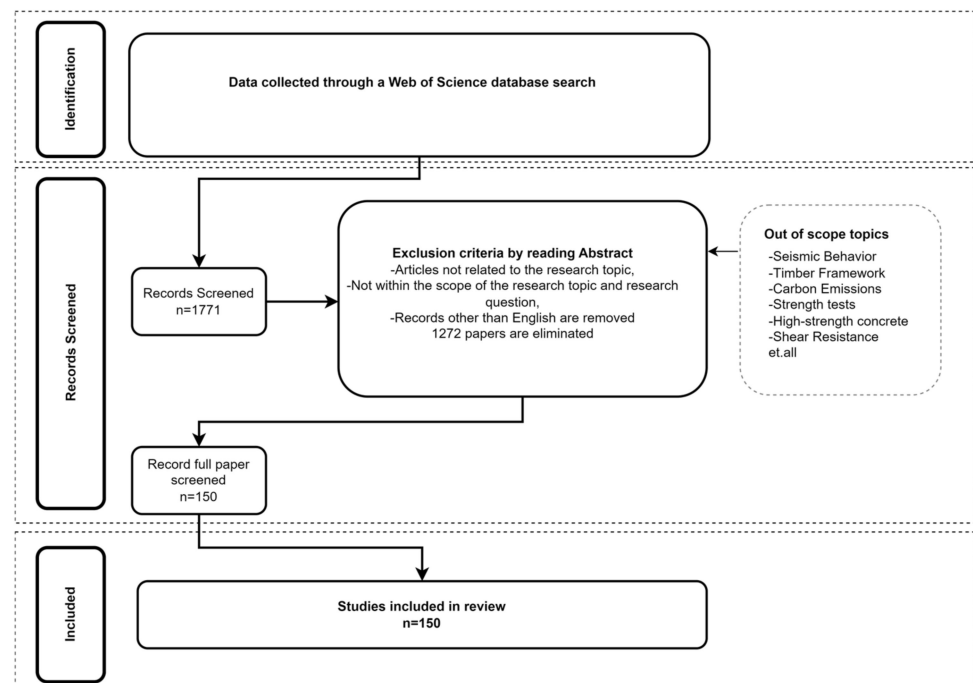

Figure 2. Data collection process.

After reviewing the abstracts of the 1771 retrieved papers, 1272 papers were excluded from the selection as they were found to be unrelated to risk. In this screening process, non-English papers and those without full text were also removed. Subsequently, a total of 150 articles remained, and these were further analyzed in their entirety to be used as data for bibliometric analysis (Figure 2).

2.1.4. Bibliometric Analysis

The final phase of this study involves conducting a bibliometric analysis to create a comprehensive map of the research landscape. This mapping analysis serves multiple purposes, including understanding the relationships between sources, summarizing existing knowledge, identifying knowledge gaps in the field, revealing themes and trends in the existing literature, and utilizing previous studies to identify potential research questions and to guide future studies.

In terms of bibliometric analysis, a variety of software platforms (e.g., VOSViewer, CiteSpace, SciMAT, CoPalRed, Bibexcel, and so on) can be utilized [73]. However, due to the cumbersome nature of most of the bibliometric analysis processes performed with these programs, they are not useful for researchers to analyze the literature [65]. In contrast, Bibliometrix sets itself apart as a recently developed software package based on the R-environment, offering higher adaptability and integrating graphical functionalities from other bibliometric tools. This study leveraged the flexibility and capabilities of Bibliometrix within R Studio to conduct a comprehensive bibliometric analysis of the PCRs research area.

As seen in Figure 1, this stage consists of both metrological and content analysis. The metrological analysis involves examining the general characteristics of the literature, including active countries' contributions and journal citation patterns, to gain an overview of the PCR domain. On the other hand, content analysis focuses on keyword frequency, keyword mapping, keywords' chronological change tendencies, thematic analysis, and cluster analysis to reveal the intellectual structure of the PCR research field. These analyses

not only provided insights into the current situation but also enabled the identification of future trends in the subject area. Overall, this integrated approach allows for a thorough examination of the PCR research landscape, shedding light on the field's development and direction.

3. Results

3.1. Evaluation of Retrieved Data

The 150 articles obtained after the screening process are uploaded to the R program for analysis, and a thorough examination is conducted to identify any missing information in the dataset. The investigation revealed that crucial information such as "abstract", "author", "document type", "language", "number of citations", "publication year", "scientific categories", "title" and "total citations" has no data loss while where was minimal data loss of less than 1% in the fields of "link", "cited sources", and "responsible author". However, a data loss of 20% was detected in keyword and keyword plus data (Figure 3). The reason behind the missing keyword data appeared to be the authors' failure to input keywords into the journal system. In our study, articles without keywords were excluded from the keyword analyses. However, they were still considered and utilized in all other analyses conducted.

Metadata	Description	Missing Counts	Missing %	Status
AB	Abstract	0	0.00	Excellent
AU	Author	0	0.00	Excellent
DT	Document Type	0	0.00	Excellent
SO	Journal	0	0.00	Excellent
LA	Language	0	0.00	Excellent
NR	Number of Cited References	0	0.00	Excellent
PY	Publication Year	0	0.00	Excellent
WC	Science Categories	0	0.00	Excellent
TI	Title	0	0.00	Excellent
TC	Total Citation	0	0.00	Excellent
C1	Affiliation	1	0.67	Good
CR	Cited References	1	0.67	Good
RP	Corresponding Author	1	0.67	Good
DI	DOI	15	10.00	Good
DE	Keywords	26	17.33	Acceptable
ID	Keywords Plus	30	20.00	Acceptable

Figure 3. Evaluation of the data uploaded to the R program.

3.2. Overview of PCRs Research

3.2.1. General Features of the Literature

Figure 4 shows the graph of annual risk-related publications in PC between 2000 and 2023 for 150 articles obtained from the WoS database. The first study in this area was conducted in 2000, but then there were no studies in this area until 2010. After 2014, this study topic started to trend again. Although the number of studies published in this field has decreased in some years, a generally increasing trend is seen until 2022. The study topic reached its maximum in 2022 with 50 articles. It is seen that citations have a general upward trend until 2019, but a rapid decline is observed in 2020. This can be attributed to the fact that the interest in the construction sector has shifted to PC due to the COVID-19 pandemic [74,75]. As can be seen in Figure 4, the annual average citation

rate and the number of publications per year show a similar pattern with a difference of 2 years. The time lag, characterized by citations being two years ahead of publications with a similar pattern, can be attributed to various factors, including preprint sharing, rapid online publication, early access availability, citing unpublished works, quick review and publication processes, and the early influence and impact of highly influential research.
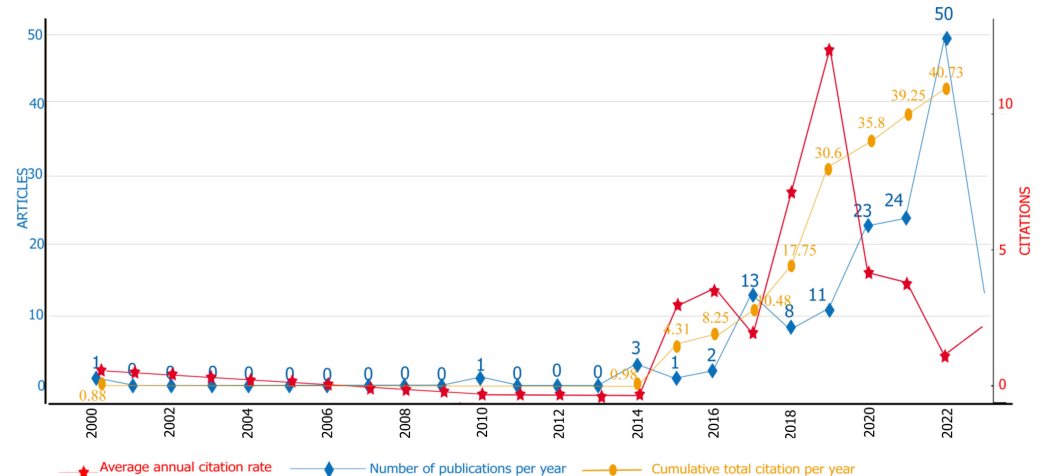

Figure 4. Annual scientific production.

3.2.2. Active Countries Analysis

A comprehensive analysis of the data obtained from the R program reveals that a total of 16 countries have been actively involved in research on risk in prefabricated structures. Figure 5 presents the nine leading nations based on the number of publications, recorded as the program's statistics. In Figure 5, the bar chart is color-coded to represent distinct publication types. The blue bars indicate "Single Country Publications (SCP)", referring to studies conducted solely by one country. Conversely, the red bars signify "Multiple Countries Publications (MCP)", indicating collaborative research efforts between multiple nations. This visual representation aids in understanding the distribution of publications across different collaboration patterns in the field.
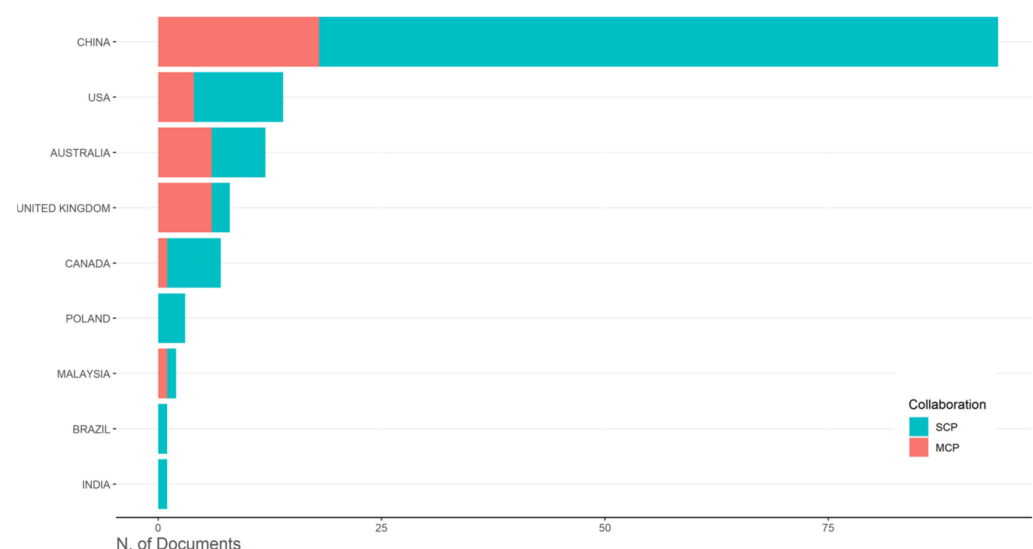

Figure 5. Number of articles based on the countries.

Table 2 presents numerical data corresponding to the illustrated information in Figure 5. China has published significantly more publications than other countries. It

is important to note that the analysis encompasses Hong Kong under the umbrella of China, which contributes to its inclusion as a part of China in the overall assessment. The fact that the studies conducted in China and Hong Kong are more than other countries can be attributed to the fact that these countries have a large population, and the governments of these countries require the use of prefabricated units with standard modular integrated design for all mass housing projects [24,30]. Although China is the country that has published the most articles numerically, it is among the least collaborative countries proportionally. This shows that the studies on this subject are mostly carried out within the country. Again, the USA and Canada are among the countries that collaborate less proportionally, while Poland, Brazil and India have no collaboration. On the other hand, the UK is proportionally the most collaborative country.

Table 2. Total number of publications (articles), single country publications (SCP), and multiple countries publications (MCP) by country.

Country	Articles	SCP	MCP	MCP/SCP Ratio
CHINA	94	76	18	0.23
USA	14	10	4	0.40
AUSTRALIA	12	6	6	1
UNITED KINGDOM	8	2	6	3
CANADA	7	6	1	0.16
POLAND	3	3	0	0
MALAYSIA	2	1	1	1
BRAZIL	1	1	0	0
INDIA	1	1	0	0

3.2.3. Journal Source Analysis

A thorough investigation was conducted to identify the primary journals where the 150 articles related to risk in PC from 2000 to May 2023, obtained from the WoS Database, were predominantly published. The journal that has accepted the most publications in this field in the last 10 years is the "*Journal of Construction Engineering and Management*", with 16 publications and followed by "*Buildings*" with 15 publications. The "*Sustainability*" journal published ten papers, while the journal "*Engineering, Construction, and Architectural Management*" has added eleven papers to the body of literature (Figure 6).

Figure 7 shows the analysis of the distribution of resources according to Bradford's Law taken from the R program. This law states that papers published by scientists on a topic are usually concentrated in a limited number of journals and less concentrated in other journals. Bradford's Law, which is used in bibliometric analysis, can help scientists determine which journals they should focus on in their literature search [76]. In this respect, several journals emerge as the focal point for the research in the field of PCRS. These journals include "*Journal of Construction Engineering and Management*", "*Buildings*", "*Engineering Construction and Architectural Management*" and "*Sustainability*". Researchers can leverage these journals to acquire valuable insights into the domain of PCRs. The esteemed journals, namely the *Journal of Construction Engineering and Management, Buildings, Engineering Construction and Architectural Management,* and *Sustainability*, have been accepting articles covering various topics, including sustainability, energy efficiency, waste management, and building management. These topics align closely with the subject of prefabricated buildings, leading to a notable correlation with the high acceptance rate of research papers in these journals.
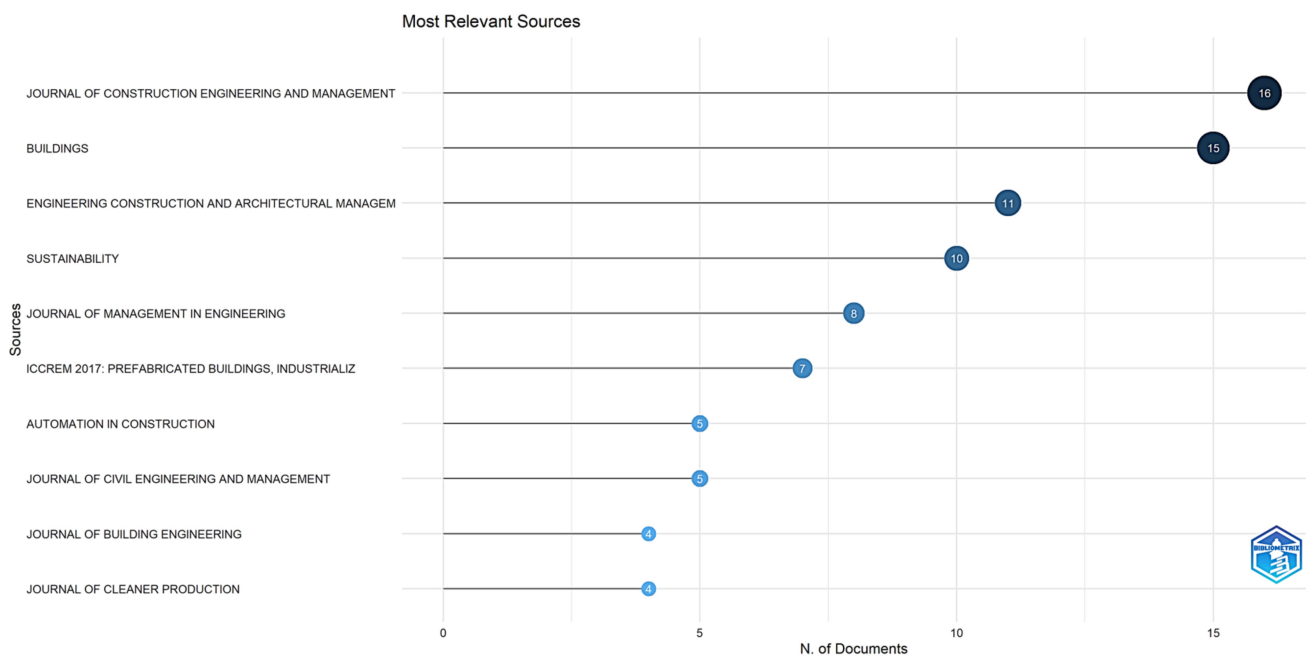
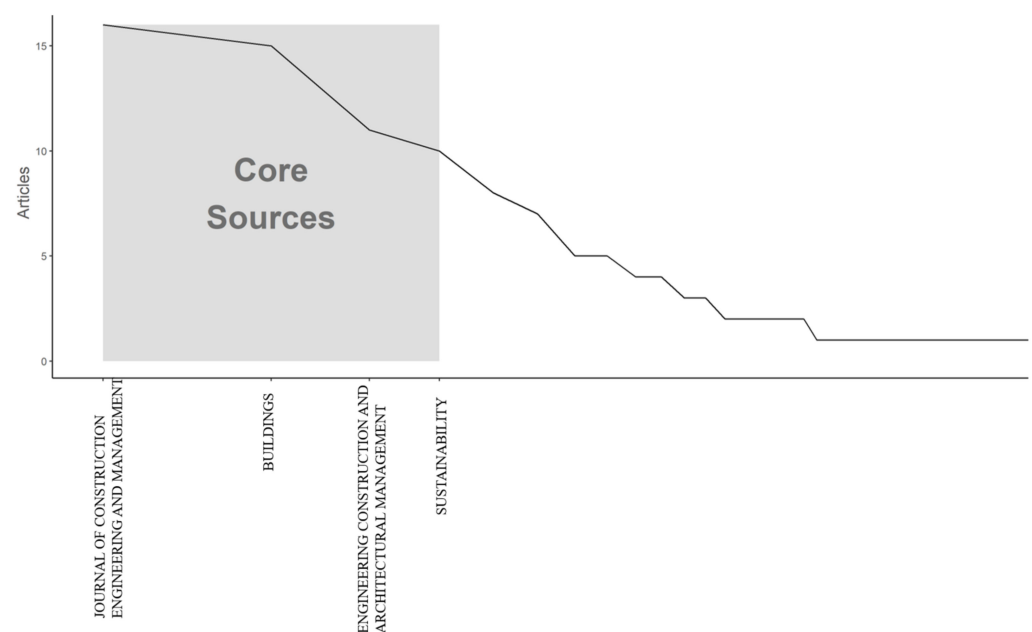**Figure 6.** The top 10 most relevant sources publishing PC risk articles.

Figure 7. Bradford's Law analysis for PCRs.

3.2.4. Leading Researchers

The leading authors in the PCRs domain are determined using the author information included in the collected data. Table 3 provides essential metrics, including the *h*-index, total citations (TC), number of publications (NPs), and the year of their first publication in the PCRs area (PY-start) for the top 10 notable authors who have made significant contributions to PCRs publications. According to Table 3, Shen GQ is the most influential scholar in PCRs domain, since his *h*-index, TC, and NP are all the highest. In terms of *h*-index, he is followed by Arashpour M, Li Cz, Li XD, and Wuni IY. In addition, we conclude that The Hong Kong Polytechnic University is the institution with the most effective studies in the field of PC.

The reason why institutions in and around Hong Kong have recently conducted more studies in the field of PC is thought to be that the Hong Kong government has implemented mandatory regulations and incentive programs in the field of prefabricated construction [30], which has encouraged researchers in this direction. The results in Table 3 also support this fact.

Table 3. Top 10 influential researchers in the PCRs research domain.

Author	*h*-Index	TC	NP	PY-Start	Academic Institution
SHEN GQ	6	434	8	2018	The Hong Kong Polytechnic University
ARASHPOUR M	4	106	5	2016	RMIT University
LI CZ	4	280	5	2018	Shenzhen University
LI XD	4	34	4	2018	Tsinghua University
WUNI IY	4	77	5	2020	The Hong Kong Polytechnic University
EL-ADAWAY IH	3	73	4	2020	Missouri University of Science and Technology
HAN YH	3	80	3	2017	Chang'an University
HONG JK	3	235	3	2018	Chongqing University
LI X	3	245	3	2018	The Hong Kong Polytechnic University
LIU Y	3	33	9	2017	North China University of Technology

Figure 8 illustrates the research output of these authors over time. The size of the spheres in Figure 8 indicates their volume, which grows proportionally with NP (number of publications) each year. Notably, Shen GQ and Li CZ achieved the highest TC/Y ratio (31.00) in 2018, followed by El-Adaway IH and Nabi MA (10.00) in 2020, and LIU Y in 2022 (8.50). These results suggest that their research output in the relevant years had a greater impact compared to other scholars to some extent. Furthermore, upon closer examination of Figure 8, it becomes evident that author's interest in PCRs has significantly grown between 2020 and 2022. This observation aligns with the findings of the literature reviews and current events, indicating that the onset of the COVID-19 pandemic in 2019 led to an increased demand for emergency hospitals and care centers [74,75]. Accordingly, government policies have changed and the tendency towards prefabricated construction has increased [30]. Therefore, studies in the field of prefabricated construction have also increased. Figure 8 also supports this fact.
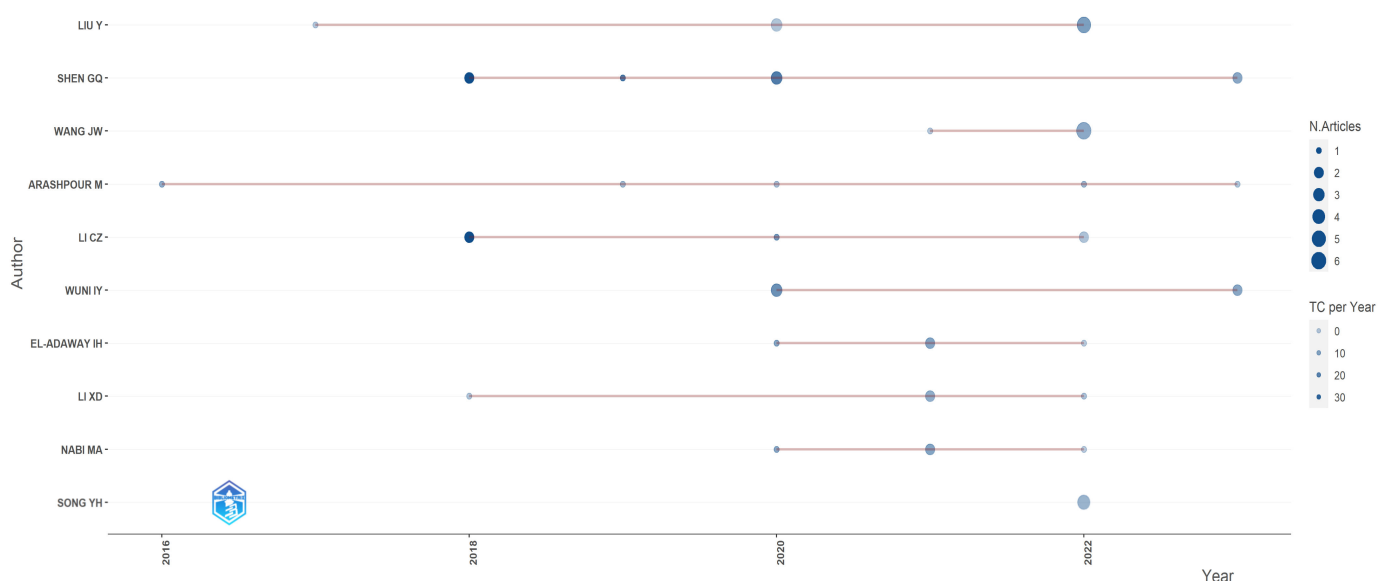

Figure 8. Top 10 researchers' production over time in the PCR research domain.

3.3. Intellectual Structure of the PCRs Domain

Bibliometric analysis is well suited for condensing large volume of literature into easy-to-understand insights. As Aria and Cuccurullo [65] asserts, bibliometric analysis provides valuable understanding of the "intellectual structure" the research field. Therefore, a series of bibliometric methods (keyword analysis, cluster analysis, thematic evaluation and trend topic analysis) are adopted to present the intellectual structure of this domain as part of content analysis.

3.3.1. Keyword Analysis

In this section, various network analyses are conducted. Network analysis is a crucial technique for determining the structural relationships among the key factors in a bibliometric analysis. In this study, keyword and keyword plus analysis, thematic network analysis, cluster analysis and trend topic analysis were conducted.

Within the scope of the study, 445 keywords identified in 150 articles are used for bibliometric analysis. The most frequently used 50 keywords are presented in Table 4. Upon analyzing the keywords in Table 4, it becomes apparent that there are synonyms or words that have similar meanings. The existence of such overlapping words may lead to inaccuracies in keyword analysis. Fortunately, unlike other bibliometric analysis programs, R-tool has a capability to merge such words, mitigating the potential issues in our study.

Table 4. The most frequently used 50 keywords in the data set.

Words	Occ.	Words	Occ.	Words	Occ.	Words	Occ
prefabricated construction	15	china	4	literature review	3	industrialized construction	3
prefabricated building	12	construction	4	modularization	3	influencing factors	3
prefabricated buildings	11	construction industry	4	off-site manufacturing	3	decision support	2
risk management	11	construction safety	4	review	3	delay	2
modular integrated construction	7	hong kong	4	risk identification	3	developing countries	2
modular construction	6	logistics	4	supply chain	3	discrete event simulation	2
off-site construction	6	stakeholder	4	analytic hierarchy process	2	ergonomics	2
offsite construction	6	barriers	3	bayesian network	2	game theory	2
prefabrication	6	bim	3	building information modeling (bim)	2	general contracting mode	2
risk assessment	6	building information modeling	3	case study	2	grounded theory	2
supply chain management	6	critical success factors	3	challenges	2	implementation	2
risk	5	dematel	3	construction management	2	construction projects	2
system dynamics	5	digital twin	3	risks	2		

Recognizing that synonyms can introduce deficiencies in bibliometric analysis, we combined the words having similar meanings under the umbrella of their representative words, as presented in Table 5, to enhance the accuracy of our keyword analysis.

Table 5. Matched words.

Word	Consignification
prefabricated construction	prefabricated building; prefabricated buildings; modularization; off- site manufacturing; modular construction; modular buildings; off-site construction; offsite construction; prefabrication; modular integrated construction
bim	building information modeling (bim); building information modeling
barriers	challenges
risk	risks

3.3.2. Frequently Used Keywords

Table 6 shows the most frequently used keywords and frequency of their use in the articles studied in the field of PCRs. The significant prevalence of the term "prefabricated construction" can be attributed to the combination of a large number of words with similar meanings, all grouped under the keyword "prefabricated construction". This aggregation has led to the high frequency of this specific keyword in the results. At the same time, it is obvious that the keyword "prefabricated construction" is predominantly followed by the keywords related to "Risks". This observation aligns with the central focus of our work, which is related to investigating the risks associated with prefabricated construction.

Table 6. Frequently used words in the field of PCRs.

TERM	f
prefabricated construction	76
risk management	11
bim	8
literature review	6
risk	6
risk assessment	6
supply chain management	6
barriers	5
system dynamics	5

3.3.3. Keyword Mapping Analysis

After grouping and merging the synonyms, keyword mapping is conducted. Keyword mapping aims to find scientific research's structural and dynamic aspects using a knowledge structure. Figure 9 shows the network of keyword plus association of publications on PCRs. The diameter of the circles indicates the number of times a word occurs in the sample, the ties between them indicate the words used together, and the thickness of the ties indicates the number of times these words are used together in a publication. The colors represent the word groups with the strong associations.

The keywords of the article are determined by the authors; keyword plus is defined by the indexers to better describe the content of the article. In keyword mapping analysis, keyword plus data are utilized. The Walktrap algorithm [77], renowned for its effectiveness in community detection on terms, is employed for creating the co-occurrence network to illustrate keyword mapping. This algorithm analyzes the structure of a given term, creates nodes, divides them into groups and groups similar nodes together in the same community [77]. A system of links connects the words that appear together in an article. By visualizing this co-occurrence network, the association of the risks in the context of

prefabricated construction (PC) research is demonstrated, shedding light on its underlying patterns and relationships.
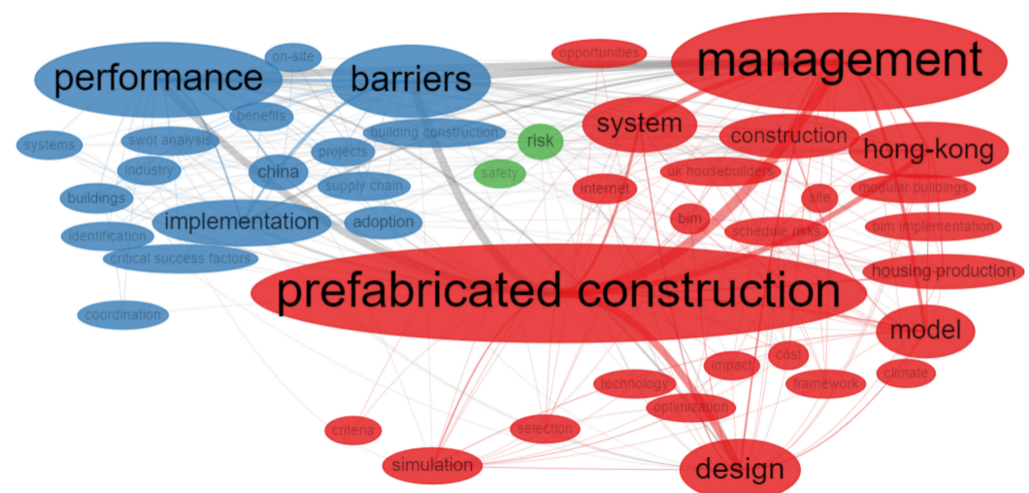

Figure 9. Co-occurrence network with keyword plus.

From the keyword analysis in Figure 9, it is seen that the word "prefabricated construction" is strongly associated with the words "management" and "performance". In addition, it is observed from the graph that China, which performs the most studies in this field, conducts more research on performance, while Hong Kong conducts the most studies in the field of management. When the illustration is evaluated from a similar perspective, it is seen that the words, barriers and implementation, are strongly associated with the performance-related research. The fact that the words, risk and safety, are in a different color from the others can lead to the conclusion that these terms are directly related to each other and indirectly related to other keywords.

3.3.4. Temporal Trends of Keyword

To better understand the evolution of topics over different time periods, we analyze the keyword trends during the span of 2013 to 2023. Figure 10 illustrates the temporal frequency of keyword usage, providing valuable insights into how these keywords have been employed over time. The most used keywords in the dataset were "management, performance, barriers, design and implementation". When this result was analyzed, it is seen that the first study in this field started with the word "design" in 2016, followed by the words "management" and "performance" in 2017. In 2018, the words "barriers" and "implementation" were included in the domain. In the same year, the term "design" was used more than other terms in prefabricated construction. Afterwards, the word "management" has gained the fastest momentum between 2019 and 2023. The term "implementation" has been used less than "management, performance, barriers and design" over all period of the time in the graph. In 2023, the word "Management" have the highest attention, followed by "Performance", which gained momentum compared to the other keywords.

The adoption of modular systems in design and application has proven to be advantageous, simplifying the implementation and design efforts [3,78]. This situation is thought to lead to relatively less research in design and application. However, the management of prefabricated buildings is still a complex process. For this reason, research on the management of PC is widespread [61]. Figure 10 supports our arguments.
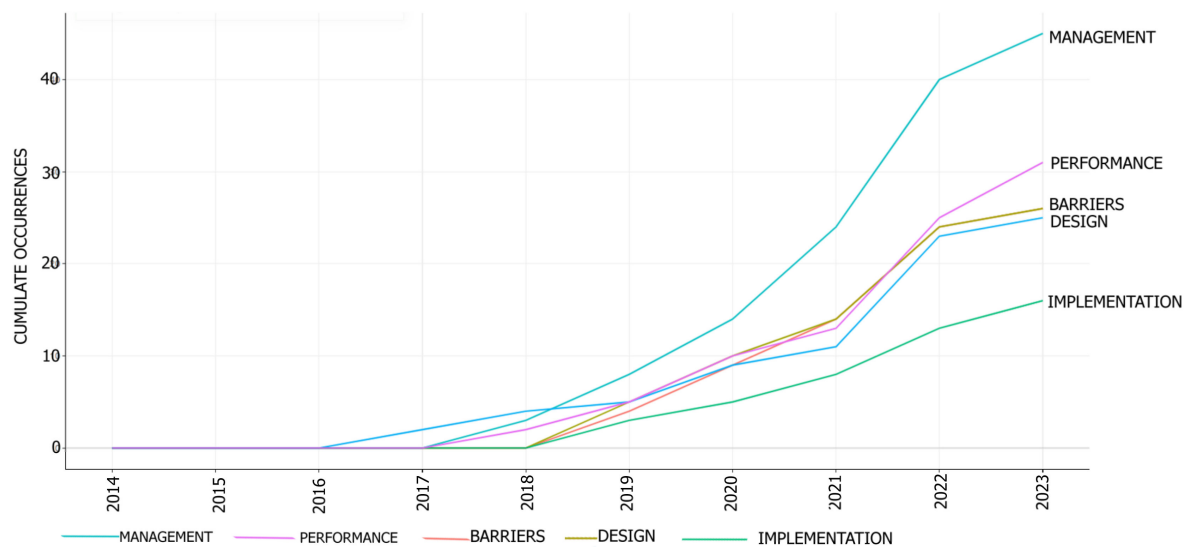
Figure 10. Cumulative occurrence by keyword.

3.3.5. Thematic Network Analysis

Thematic mapping is a method of analysis that enables examination of the effects of concepts learned in the field (Figure 11). Thematic mapping is used to make a classification by projecting the keywords in the studied dataset onto the two-dimensional system [76]. In the diagram in Figure 11, the circles represent sets of words that are related to each other. The size of the clusters' circles directly corresponds to the number of publications on this subject. In this diagram, the vertical axis represents density and the horizontal axis represents centrality [79,80]. The density shows the relationship between the themes in the circle. In other words, if the relationship of the words in the cluster is high, the cluster is directed upwards in this diagram. In addition, the density also shows the development capacity of the words. Centrality shows the interaction of a cluster with other clusters. That is, as the relationship of a cluster to other clusters increases, the cluster is orientated to the right [79,80].

When the results are projected onto the strategic diagram, the motor theme, identified as quadrant I in Figure 11, represents themes of high centrality and high intensity. This means that words in this area are crucial and have significant potential for progress and impact. Niche themes, defined in quadrant II of the chart, are of low centrality and high intensity. That is, they are highly specialized themes but may not have the appropriate background or may no longer be considered important due to newly emerging concepts or for various reasons. Emerging or diminishing themes are also identified in quarter III. They have low centrality and low intensity. In other words, These themes are characterized by infrequent appearances or potential decline. A qualitative analysis is necessary to accurately determine their trajectory, distinguishing between emerging and declining patterns. Basic themes, defined in quarter IV, are themes of high centrality and low intensity, i.e., themes that are relevant to the research area but are not extensively explored yet. Despite this, they tend to be motor themes due to their high centrality [76,79,80].

Upon analyzing the clusters, certain concepts like "dematel", "delay", "grounded theory", and "ISM" while other group of topics such as "BIM", "barriers", "stakeholders", and "critical success factors" have emerged as examples of motor themes. It means that they contributed the most to the development of the field with both internal and external associations. Within the two groups of concepts, "BIM", "barriers", "stakeholders", and "critical success factors" are identified as more closely associated with other clusters. Additionally, these concepts exhibit a higher number of publications compared to the other group, considering the discrepancy in cluster size between groups.
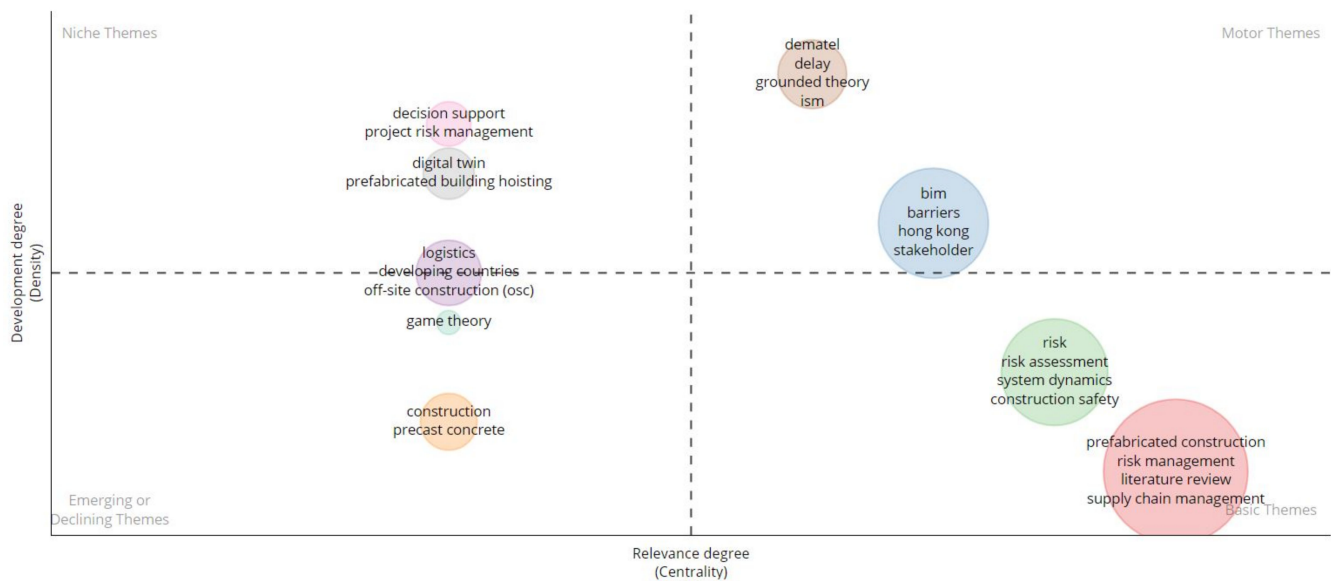
Figure 11. Thematic mapping.

"Decision support", "project risk management", "digital twin", "prefabricated building hoisting" are seen as examples of niche themes in the second quarter. It means that they are highly developed but at the same time, they are isolated themes. Although they had strong relationships among themselves, they are not significant for PCRs research.

Emerging or diminishing themes, "game theory", "construction" and "precast concrete" are seen in the third quarter of this analysis. They have low significance. After analyzing all clusters in the II and III quadrants, it becomes evident that they form a nearly vertical alignment, indicating a similar degree of association with other variables over time, while their development diverges in accordance with internal associations. Among them, the theme consisting of "decision support" and "project risk management" has the highest internal associations. In addition, it is evident that the "game theory" theme has made the least contribution in PCRs domain based on its cluster size.

The fourth quadrant shows the basic themes, in other words, concepts that are important for the field but not sufficiently developed. "Risk", "risk assessment", "system dynamics", "construction safety", "prefabricated construction", "risk management", "literature review", and "supply chain management" are shown as the main themes in the data set used in the study. Although the clusters in this quadrant have weak relations within themselves, they are intensely related to other clusters. When the cluster size is considered, it can be concluded that most publications use the words in these clusters.

3.3.6. Cluster Analysis

This study employs cluster analysis to explore the presence of distinct groups within the dataset. K-means clustering is deployed using the correlation analysis of the co-citation matrix. In order to determine the optimal number of clusters, k = 2, k = 3, k = 4, and k = 5 values are given, respectively, as seen in Figure 12. It is observed that there is only one element under the cluster at k = 5, but this is not sufficient to form a cluster. The application of the K-means clustering algorithm with k = 4 in this study resulted in the formation of meaningful groups.

Figure 12. Cluster detection for database.
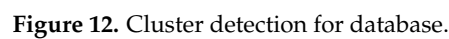
According to the clustering created as a result of the K-mean analysis, Cluster 1 is defined as "Management", since it contains more words related to management. Cluster 2 is defined as "Schedule" due to its focus on scheduling-related terms, Cluster 3 is defined as "Logistics" and Cluster 4 is defined as "Supply Chain". In addition, Table 7 shows the resources that contributed most to the establishment of the clusters.

Table 7. The most effective sources for the formation of clusters.

Cluster 1 "Management"	Cluster 2 "Schedule Risk"	Cluster 3 "Logistic"	Cluster 4 "Supply Chain"
[81]	[82]	[83]	[84]
[85]	[86]	[87]	[88]
[89]	[21]	[90]	
[91]	[92]	[25]	
[93]	[10]	[1]	
[2]	[94]		
[7]	[12]		
[95]	[50]		
[37]			
[96]			

3.3.7. Thematic Evaluation

Within the scope of the study, the articles in the database are analyzed and presented in three area graphs and the relationships between them are highlighted through the Sankey diagram in Figure 13. Sankey diagrams, known as thematic evolution tools, are essential for representing flow in various networks and processes [97]. By observing these diagrams, the evolution of processes and intellectual relationships within the field becomes apparent, offering valuable insights into the subject's development over time. The study incorporates thematic evaluation, a crucial aspect that examines whether key concepts in the field have evolved throughout the years. This evaluation provides a deeper understanding of how these concepts have transformed and adapted [98]. The research explores the evolution of prefabricated construction research (PCR) across three distinct periods: early 2000–2020, 2021–2022, and after 2022. PCR started in the early 2000s. In general, when starting scientific research, due to time and economic reasons, a study starts with a general framework, moving on to conducting impact analysis in the field and simulations. Consequently, during the early 2000s, the focus of prefabricated construction research was centered around exploring themes such as "prefabricated construction", "impact", and "simulation". After the initial stages of research, the natural progression involves expanding and delving deeper into the field. Over the course of time, the term "prefabricated construction" has undergone a notable evolution, encompassing diverse themes such as "management, risk, safety, adoption, model, Hong Kong, behavior, BIM" in the period of 2021–2022. In addition, the emergence of the COVID-19 pandemic and the effects of some governments' incentives for prefabricated structures are seen between 2021 and 2022 as explained in Section 3.2.1. We anticipate that the rapid increase in demand for prefabricated construction due to COVID-19 highlighted the importance of addressing "Management" issues as a crucial point for effective mitigation strategies. Figure 13 reflects our arguments. Since all the works in 2023 have not been completed, the final trends of the works have not yet been reflected in the graph. However, the works carried out this year generally show a trend towards management, construction and performance (Figure 13).
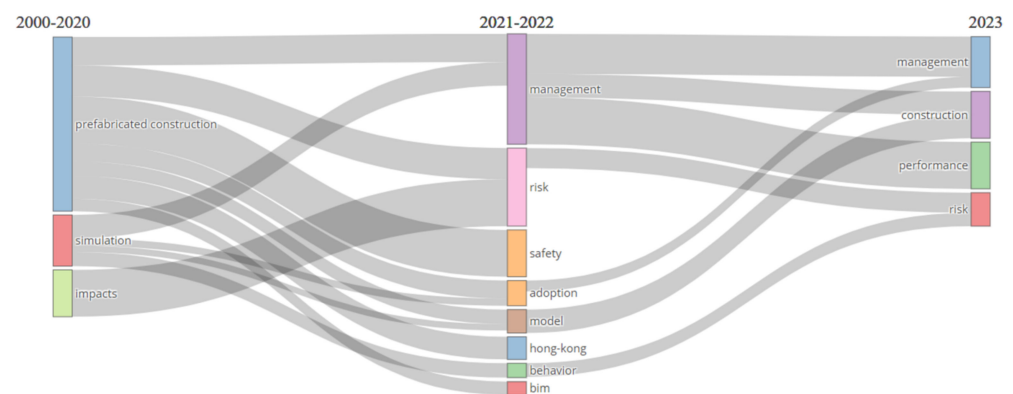
Figure 13. Thematic evaluation of PCRs research (2000–2023) with Sankey Diagram.

3.3.8. Citation Analysis

Citation analysis is used here to discover and explore the most commonly cited publications in the PCRs domain, as well as their relationships; it is a widely used method to investigate the underlying intellectual structure of a research topic. Table 8 lists the top ten most cited publications in the PCRs area, as well as their global citations (GCs) in descending order by number of local citations (LCs). The number of times a document is cited by papers in the collected data set (i.e., the set of 150 documents) is referred to as LC, and it can be used as a metric to indicate the influence of these papers in the PCRs research field. GC, meaning the number of times a paper is cited in the WoS core collection database, indicates its influence in the WoS core collection database circle. It is clear that Luo [24] received the most significant LC (21) and Li [1] received the most GC (186), both of which are much higher than the remaining records. To eliminate the impact of these articles' publication years, the metrics Total Local Citations per Year (TLC/Y) and Total Global Citations per Year (TGC/Y) are employed to demonstrate the influence of these publications. In particular, Li [99], Luo [84], Luo [24], Li [1], Jiang [100], and Arashpour [92] were rated in the top five in terms of TLC/Y, showing that these articles are, to some extent, the most significant papers in the PCRs research field.

Table 8. Top 10 local cited papers in PCRs domain.

Author	Journal	Year of Publication	LC	GC	TLC/Y	TGC/Y	Topic
LUO LZ	Journal of Management in Engineering	2019	21	112	3.21	1.74	Supply Chain Risks in PC
LI CZD	Journal of Cleaner Production	2017	19	130	7.97	8.33	Integrating BIM to mitigate PCRs
LI CZ	Automation in Construction	2018	14	186	2.33	4.26	IoT-enabled PC
ENSHASSI MSA	Journal of Management in Engineering	2019	13	46	1.99	0.72	Tolerance -Based Mitigation Strategy for PCRs
LUO LZ	Journal of Management in Engineering	2020	13	55	4.33	3.07	Supply Chain Management as PCRs

Table 8. *Cont.*

	Document		LC	GC	TLC/Y	TGC/Y	Topic
Author	Journal	Year of Publication					
JIANG L	Sustainability	2018	12	54	2.00	1.24	Constraints on the Promotion of PC
ARASHPOUR M	International Journal of Project Management	2016	8	63	2.00	2.00	Interacting PCRs
LI CZ	Journal of Cleaner Production	2018	8	35	1.33	0.80	Schedule Delay Risk of PC
HSU PY	Automation in Construction	2019	8	36	1.22	0.56	Risk-averse Supply Chain for PC
WANG ZL	Sustainability	2019	8	31	1.22	0.48	Risks in PC

3.3.9. Trend Topic Analysis

Trend topic analysis is an analysis that shows which key concepts are more common in publications in particular years. Figure 14 shows that risk research in prefabricated construction in recent years has been trending in the topics of prefabricated construction, BIM, literature review, supply chain management, barriers, risk management and risk. In Figure 14, it is apparent that the main focus had been on the topic of "risk" until 2020 [85] and studies on risk management have been carried out after 2020 [101]. Additionally, there was an emergence of keywords related to "supply chain management" and "BIM", which are generally associated with the field of management. This suggests that most of the studies in PCRs tend to be associated with management-related aspects. Moreover, the appearance of the literature reviews after the definition of risk concepts indicates a trend of conducting more general evaluations on the subject. This approach provides comprehensive insights into the overall landscape of risk research in prefabricated construction.
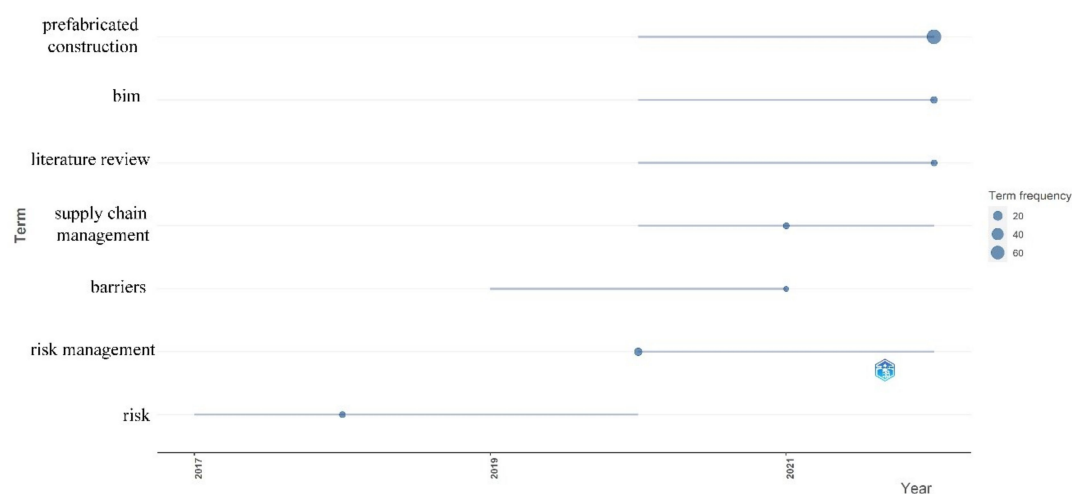

Figure 14. Trend topics.

4. Discussion

In the Architecture, Engineering, and Construction (AEC) industry, prefabricated construction (PC) is considered as a superior alternative to traditional construction methods due to its advantages. However, it is known that PC has several significant risks, which is why to foster its growth and improve its efficiency, it is crucial to identify and assess these risks. Such risk assessing approaches will increase both the tendency towards the

use of PC and enhance the overall quantitative efficiency of PC [10]. Although there are significant research on PCRs studies, bibliometric research on the PCRs literature is still lacking, thereby preventing researchers' access to more extensive, diversified, and detailed information of this domain. Unlike former bibliometric and review studies, this study extends the bibliometric journey by undertaking a broad metrological and content analysis of the PCRs research area. The overview of PCRs research is presented using a recently developed Bibliometrix R-package tool, and the intellectual structure of this subject is investigated using content analysis. In general, when bibliometric analyses in the literature are examined, it is seen that words with similar meanings in keyword analysis create many nodes and cause various confusions. To avoid this complexity, in this study, similar words are merged in keyword analysis, as suggested by Aria and Cuccurullo [65].

This study is based on a comprehensive, dependable, and high-quality dataset that includes 150 journal articles about PCRs published between 2000 and 2023 and obtained from the WoS database.

The review of PCRs research is depicted from different perspectives encompassing the annual number distribution, most influential countries, leading researchers, and journals in the PCRs field.

(1) Although PC research has been in existence for a long time, PCRs-related studies started to gain momentum in 2014 and peaked in 2022, which shows that risk awareness in PC has started to increase in the last five years (Figure 4).

(2) According to the most influential country analysis, the country that has conducted the most work in this field is China (Figure 5). Li et al. [61] state that this situation is due to the high need for industrialized construction sector in China. Additionally, Table 2 reveals that the UK stands out as the most collaborative country proportionally.

(3) The analyses in this study identify "*Journal of Construction Engineering and Management*", "*Buildings*", "*Engineering Construction and Architectural Management*" and "*Sustainability*" as the most prominent and utilizing the Bradford's Law method, it has been determined that they are highly significant and valuable sources for researchers who work on this subject (Figures 6 and 7).

(4) Shen GQ is the most noticeable researcher in the PCRs domain followed by Arashpour M, Li Cz, LiXd, and Wuni IY in terms of the *h*-index.

In terms of the intellectual structure of the PCRs domain, keywords analysis and citation analysis are coupled to uncover the key components of this field's knowledge base. To highlight the foremost semantic topics hidden in textual data and reveal the thematic evolution of the PCRs domain, keywords analysis, change in the top 10 keywords by frequency, conceptual structure map, co-occurrence network with time information, strategic diagrams, and Sankey diagrams are represented.

(1) One of the unique aspects of the current study compared to former bibliometric analyses is that it performs keyword plus analysis. While keywords are determined by the researchers, keyword pluses are attributed by indexers for a better understanding of the theme, subject and content of each retrieved papers. In this study, keyword pluses are used since research was conducted on the content of the articles. The research around "management", "performance", "barriers", "design" and "implementation" are identified as areas of significant interest in future research, given their apparent increase in attention over time. (Figure 10).

(2) Thematic mapping and thematic evaluations were also carried out to elaborate the study and develop ideas for the future. Figure 11 illustrates the thematic mapping process, which shows that the most central area of research on the topic were the emerging themes of BIM (Building Information Management), barriers and stakeholders in the motor theme. Furthermore, dematel, grounded theory and ism were identified as the most developed methods. With the integration of the PC with BIM, existing technologies can be improved, barriers of the work area can be identified in advance, additional costs can be avoided and area safety can be increased [102].

(3) Since merely keyword analysis does not provide a clear analysis, clustering analysis was performed with the K-means method in this study. This method is one of the unique features of this study compared to other bibliometric analyses. Unlike former studies, conceptual clusters were created by applying the K-means method through the keyword plus network. Figure 12 illustrates the results of multiple attempts to determine the optimum number of clusters, revealing that four clusters were identified as the most suitable outcome. Following a thorough evaluation of the terms within each cluster, the four clusters were appropriately named as follows: (i) management risk, (ii) scheduling risk, (iii) logistic risk, and (iv) supply chain risk.

i. Regarding Management Risk: The importance of management in preventing risks during the production and application processes of prefabricated structures is vital [81]. According to Koç and Gurgun [103], failures that may occur in prefabricated structures can be prevented with the right management and management strategies. Wu et al. [85] produced statistical data through a survey study with experts in order to identify gaps in PC practices. The study concluded that there are still gaps in the management of risk assessment in prefabricated construction and that this area should be supported by more case studies and empirical studies. Xi et al. [93] conducted a case study on the assessment of risks in prefabricated buildings and concluded that effective management has significant value in the success of prefabricated buildings. All these studies show that although the management area is very important in determining the PCRs and taking precautions against risks, this area is still in need of further study.

ii. Regarding Scheduling Risk: Although one of the advantages of using PC is to produce projects in a short time, there are still many scheduling risks in prefabricated buildings [104]. When a project's completion date exceeds the specified contractual period, project delay arises [105]. Project delays are inevitable in the AEC industry [106]. According to Ji et al. [107], some of the most crucial factors contributing to PC project delays are insufficient worker expertise, poor modular component connection, inadequate stakeholder management, and low productivity. According to Li et al. [108], supply chain disruptions are the most common cause of delays in PC projects. Since modular components are constructed to order, modular production frequently involves job shop scheduling to maximize resource allocation and facilitate timely modular delivery [109]. To handle the schedule risk occurrence, Zhai et al. [110] developed the lead-time (L), space (S), and L + S hedging approaches to build a buffer against unanticipated delays, upstream supply, and modular delivery ambiguities. These hedging approaches seek to increase the reliability of modular supply to decrease schedule delays. However, because modules are made-to-order [111], advance manufacture, transshipment, and dual sourcing of PC components are less possible due to the rigid supply chain once scheduled [112].

iii. Regarding Logistic Risk: Since PC elements are manufactured off-site and assembled on-site by transport, they contain logistical parameters and associated logistical risks, in addition to the parameters in traditional structures [87]. PC logistics are vulnerable to risks in the supply chain [87]. Hussein et al. [78] developed a model for logistics planning in prefabricated buildings, taking into account the dynamic behavior and interaction between stakeholders, traffic conditions, site layout, and complex interactions between processes and the means of transport. In this study, it was evaluated in a risk-free environment, but completely real scenarios were not used. For future studies, it is important to evaluate the models with logistics of the real field work scenario in terms of the reliability of the results. In addition to all these, in future studies, the carbon emitted by vehicles in the transport of prefabricated buildings can

be evaluated to assess whether there is a risk in terms of sustainability of prefabricated buildings compared with traditional buildings.

iv. Regarding Supply Chain Risk: One of the significant parameters affecting the success of PC is the supply chain [8]. PC faces additional supply chain risks than traditional construction since it has longer chains resulting from multiple workplaces; it also requires additional and earlier design work due to prefabrication lead time and requires more precise requirements [113]. Given that supply chain risks have a significant impact on PC advancement, productivity, and efficiency, researchers have investigated supply chain risks from three distinct perspectives. To begin, the results of the game theory analysis and numerical simulation demonstrate that enhancing supply chain integration is an effective measure for reducing supply chain risks [24]. Then, as integration approaches, lean thinking and knowledge management were added to transform supply chain risks into potential alternatives [114]. Second, optimizing the supply chain design is a viable method [84]. Following that, risk-averse logistics arrangement and hybrid intelligent vehicle systems were redesigned to alleviate associated tension [29]. The final and most recent research is supply chain resilience, which is described as the supply chain's adaptive ability to forecast unforeseen events, deal with disruptions, and recover from them [23].

(4) Although PC and associated risks are not new research topics, the focus on these has accelerated in the last ten years (Figure 4). With the increase in relevant studies, PCRs research has evolved since 2014. While the most popular research topics in this field between 2000 and 2020 were "prefabricated construction, simulation and impact", it changed to "management, risk, safety, adoption, model, Hong Kong, behavior and BIM" in 2021–2022. In 2023, the most trending topics were identified as "management, construction, performance, risk". Research shows that the development of risk study in prefabricated construction is clear. In addition to this, from the analysis carried out in Figure 13, it can be concluded that the use of BIM in the field of performance, risk and management in prefabricated construction is open to further research. The trend topical analysis in Figure 14 also supports this conclusion.

5. Conclusions

This study conducts a comprehensive bibliometric analysis of 150 articles in the field of prefabricated construction risks (PCRs), using data gathered from the Web of Science spanning from 2000 to 2023. Employing the R studio Bibliometrix package, various analyses were performed, including active country analysis, journal analysis, researcher analysis, keyword analysis, frequency analysis, temporal trends topic analysis, thematic network analysis, cluster analysis, and thematic evaluation.

The primary focus of this study is a holistic examination of PCRs, which does not limit itself to specific countries or concentrate solely on a particular risk. It takes a comprehensive approach, aiming to explore the broader landscape of prefabricated construction risks without being constrained by geographic boundaries or single risk factors. One of the main objectives of this study is to supplement previous bibliometric studies on PCRs research by offering a new comprehensive and holistic view of the domain. In contrast to prior bibliometric studies on this subject, this research undertakes an in-depth metrological and content analysis of the PCRs topic from a holistic perspective, using a newly designed bibliometric methodology. A new set of indexes, which have not been used in previous studies (e.g., *h*-index, PY-start, TC/Y, MCP-Ratios, and TLC/Y), improve the level of metrological analysis, and the bibliometric techniques used in this paper (i.e., a series of methods for keyword analysis and citation analysis) broadens the depth of PCRs literature studies. This new attempt has the potential to integrate and broaden earlier PCRs literature research's bibliometric findings. This paper's research framework also serves as a guide for examining the knowledge base of other research topics.

Based on a thorough analysis and objective reasoning of the results and discussions, this study reveals significant findings regarding prefabricated construction risks (PCRs). Firstly, there has been a discernible increase in PCRs research in recent years. The high number of studies conducted in specific countries like Hong Kong and China appears to be closely linked to country policies and incentives. An interesting observation was that after 2020, there was a rapid surge in PC-related studies. This surge can be attributed to the urgent need to increase emergency building stocks in response to the COVID-19 outbreak. Furthermore, it was found that studies concerning the management and performance of risks demonstrated a significant increase after this critical period. Notably, China exhibited greater emphasis on performance-related aspects, while Hong Kong displayed intensified research efforts in the domain of risk management. So far, studies on PCRs have been clustered in the areas of management, schedule risk, logistics, and supply chain. Furthermore, there is an emerging trend in the utilization of Building Information Modeling (BIM) systems in prefabricated structures, aligning with advancements in technology. DEMATEL, ISM and grounded theory are promising topics in this domain. The PCRs topics demonstrated a strong relationship with the terms "management", "performance", and "risk" after 2022, highlighting their critical relevance and prominence in the latest research.

This study also has numerous shortcomings that will be tackled in future research. Firstly, merely peer-reviewed articles are used for analysis. Further studies may incorporate other types of academic publishing (e.g., book chapters). Secondly, data sourced from the WoS database may have limitations, prompting future researchers to explore additional databases like Science Direct or Scopus. Third, the current study evaluates PC in superstructure production but excludes risks in infrastructure and substructure. The risks that may occur in the use of prefabricated structures in the substructure are different from the superstructure and may be a potential research topic for future studies. Additionally, future bibliometric research can be conducted on the risks in transportation and assembly of PC, access to PC raw material sources, and risks in marketing.

The findings in this study collectively contribute to a deeper understanding of the evolving landscape of PCRs and hold the potential to enhance and expand upon the existing bibliometric knowledge in the PC domain. This study is anticipated to make a significant contribution by helping to convert existing information about risks in prefabricated buildings into quantitative data and by including recommendations for future studies.

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