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Review

Mapping the Knowledge Domains of Emerging Advanced Technologies in the Management of Prefabricated Construction

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Abstract: Emerging advanced technologies (EAT) have been regarded as significant technological innovations which can greatly improve the transforming construction industry. Given that research on EAT related to the management of prefabricated construction (MPC) has not yet been conducted, various researchers require a state-of-the-art summary of EAT research and implementation in the MPC field. The purpose of this paper is to provide a systematic literature review by analysing the selected 526 related publications in peer-reviewed leading journals during 2009–2020. Through a thorough review of selected papers from the state-of-the-art academic journals in the construction industry, EAT is recognised as the key area affecting the development of the MPC discipline. This study has value in offering original insights to summarise the advanced status quo of this field, helping subsequent researchers gain an in-depth understanding of the underlying structure of this field and allowing them to continue future research directions.

Keywords: emerging advanced technologies; prefabricated construction; knowledge map; literature review

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1. Introduction

Conventional production methods of buildings generally have problems such as high consumption of resources and energy, serious environmental pollution and high labour intensity [1]. The transformation and renovation of the construction industry are urgently required. As a more resource-saving, green and environmentally friendly construction method, prefabricated construction has widely been considered an alternative to traditional cast-in-place construction and, given its improved performance, it has been gradually recognised and has become the current characteristic and future development trend of the construction industry [2,3]. However, because multiple 'information islands' (e.g., poor information communication and low information transparency, etc.) exist among construction project participants, the efficiency and level of prefabricated construction management are low and, due to outdated construction technology, the performance advantages of prefabricated construction have not been fully realised; construction productivity is low and environmental pollution has become increasingly serious in construction [4,5]. Therefore, emerging technologies are needed to solve the current problems faced by the development of prefabricated construction, thereby promoting the development of construction industrialisation represented by prefabricated construction. Although many studies related to EAT research in the MPC field have been published, the types of articles are mostly concentrated in the two categories of research and perspective articles, and research on the types of review article is lacking. Furthermore, a comprehensive review that analyses these emerging technologies and studies their application status in prefabricated construction is limited. Hence, a systematic review that summarizes EAT related research in the MPC field

is an effective approach to make up for the chaotic, scattered and unintegrated research status in this field. In addition, with the increasing recognition of the importance of EAT for improving construction productivity, construction technology, technology content and protecting the environment, the academic interest in EAT in the MPC field is increasing. However, the content analysis and research on the existing literature appear to be inadequate, preventing researchers from grasping the overall evolution of research in this field. A comprehensive integration of previous publications in the MPC field can effectively help researchers gain a comprehensive understanding of this field and stimulate subsequent research on EAT in the MPC field [6].

1.1. Definition and Advantages of EAT

EAT refers to a series of advanced information technologies developed in the 21st century, characterised by technological convergence. Here, previously different technologies gradually merge and share resources to accomplish specific goals, such as the interaction of original voice, data and video technologies to create new and further efficient technologies. The core function of EAT is to provide users with the capacity to acquire, integrate, analyse, exchange and share a considerable amount of information in the MPC field. With the rapid development of EAT, such as building information modelling (BIM) technology, Internet of Things (IoT), big data, point cloud and cloud computing, accurately and efficiently exchanging and sharing a large amount of information in real time is technically possible during the MPC process, and EAT is considered the key area to improve the level of informatisation, intelligence and industrialisation in MPC. Previous research involved the terms and acronyms of various innovative technologies related to prefabricated construction management, including BIM, radio-frequency identification (RFID), IoT, point cloud, laser scanning, 3D printing, big data, cloud computing, machine learning and blockchain. In terms of the prefabrication progress of components, prefabricated construction is generally divided into four stages: (1) Design. The components are analysed, built and designed by software models. Quality, schedule and cost management are implemented during the component design phase; (2) Production. On the basis of the designed component samples and the actual requirement of the components, the components are automatically produced and processed under factory management by adopting an assembly line; (3) Transportation. The transporters manage the loading, transportation and stacking of components after the completion of production; (4) Assembly. After the components arrive at the assembly site, the assemblers guide the relevant technical application and implement the component site assembly. By taking advantage of EAT, the design, production, transportation and assembly of components can become real-time, dynamic, efficient and intelligent, considerably saving labour, time and funds and ultimately improving the benefits of prefabricated construction projects [7–9]. EAT, as a series of innovative management technologies that promotes the transformation of prefabricated construction from traditional, outdated and inefficient to advanced, intelligent and efficient, has attracted widespread attention in recent years. This widespread concern can be primarily explained by the inherent advantages of these technologies, including, but not limited to, achieving the real-time visibility and traceability of prefabricated components [10–14], low building energy consumption [15–17], reduced schedule risk [1,18,19], time- and cost-saving, efficiency improvement [2,20–22], quality control improvement [7,23,24], accelerated lean construction [25], informatisation and intelligence of management [11,13,22,26,27], low pollution, compliance with sustainability standards [28,29], high safety and health standards [30,31] and integrated and improved supply chain management [18,23,32–36].

1.2. Dynamic Development and Integration of Knowledge Disciplines

'Knowledge development is a dynamic process that often encourages particular research fields' [37]. The integration of some interdisciplinary studies promotes the formation and development of specific research fields. One example is the integration of the construction management field with blockchain technology that supports distribution, encryption

and security, promoting the intensification and security of construction information management [38]. Similarly, the integration of EAT and MPC has been a major catalyst of innovative research areas. An example is research on the intelligent logistics management of prefabricated components based on RFID and BIM [39]. EAT is considered a series of technologies that can integrate interdisciplinary collaboration, which is often used as a tool to help a particular research field. However, researchers may ignore the contribution and value of EAT to the MPC field or they only use a single technology for research to generalise and draw a conclusion about a certain research topic in this field, leading to a lack of precision, rigour and authority in the conclusions of this research topic, reducing the value of subsequent research in this field or related fields. Therefore, various technologies are often fused by some researchers to achieve research goals. For example, Li et al. [12] found that the problems of incomplete, inaccurate and untimely data exchange and a lack of real-time visibility and traceability cannot be solved by using only BIM technology in the on-site assembly services of prefabricated construction. To address these problems, the researchers integrated technologies such as IoT, BIM, RFID and virtual reality into an already designed IoT management service platform, greatly leveraging the advantages of technology convergence. On the basis of the research of Li et al. [12], Tang et al. [40] argued that, although the integration of BIM and real-time data obtained from IoT devices can greatly improve the operational efficiency of construction management, research on the integration of BIM and IoT devices remains in its infancy, and few researchers have fully understood the current status of BIM and IoT device integration. The scholars summarised five BIM–IoT device integration methods by combining new data models, web service technologies and service-oriented architecture patterns, thereby promoting the development of construction information management. The research field of the integration of emerging technologies and prefabricated construction is a real-time dynamic development process, which also determines that researchers must always pay attention to the dynamic information of the industry development in this field and continuously deepen their own theoretical research foundation. As researchers continue to deepen their research in the EAT discipline related to MPC, a systematic review of the research has received widespread attention.

1.3. Advantages of the Knowledge Map Method

Knowledge map, as a research method that can enhance communication among the entire research community and share common professional practice knowledge, has increasingly attracted considerable attention from researchers in various disciplines and professional practice fields, resulting in the increasing integration by researchers of the knowledge map into literature review writing in a specific field [41]. The research community, especially new researchers, generally considers literature review the key method for examining the research development of a particular discipline [6]. Li et al. [6] pointed out that these research reviews in the specific fields not only facilitate researchers to critically review and summarise the knowledge system of the selected research field and fill the gaps in the research field but also assist them in exploring novel and valuable research topics for further research. Compared with previous research statistical methods, knowledge mapping can integrate multidisciplinary knowledge, systematically present complex knowledge fields to users through data mining, information processing, knowledge measurement and graphics rendering, helping users find more accurate and valuable information to make a comprehensive and in-depth relevant summary [37]. By using knowledge mapping to conduct scientometric analysis of research literature, researchers can more efficiently analyse the research status of a certain field or a certain cross-field, greatly improving the academic value of literature reviews in the field.

1.4. Adoption of Visual Tools

The latest developments and emerging trends can be identified through a systematic review of existing research to encourage future research [42]. However, many studies are often conducted by manual review, causing problems such as knowledge gaps. To fill the

knowledge gaps in the literature of a specific research field and reveal the potential connections among various knowledge fields, some visual tools are used to conduct a scientific co-citation and co-occurrence analysis and depict a map of knowledge information, helping researchers gain a clear understanding of the formation, evolution and development of a specific research field. For instance, in the field of EAT related to MPC, Li et al. [37] conducted a co-citation and co-occurrence analysis of the BIM knowledge field by using a bibliometric approach and the visual texting mining tool Citespace to further improve the knowledge map of the BIM research field, helping subsequent researchers deepen their understanding of the BIM field and promoting the implementation and development of the EAT discipline in the MPC field. Similarly, to ensure the scientific and systematic knowledge information of this study, VOSviewer was used to conduct bibliometric analysis to obtain a comprehensive and systematic research status in this field.

1.5. Research Objectives of This Study

Despite the great significance of the research review for understanding and researching a certain field, such work in EAT of the MPC field has been minimal. A critical review and knowledge map of existing literature can improve our understanding of the application and development of this discipline. Therefore, this article provides a comprehensive analysis of academic papers published from 2009 to 2020, including an investigation of the current research status and a forecast of future research trends. To facilitate the development and implementation of EAT in the MPC field, the objectives of this study are to (1) provide a framework of keyword analysis; (2) identify which countries, institutions and authors are major contributors; (3) summarise the research topics of this field; (4) identify current research gaps in this field and (5) provide a framework for exploring the future research direction in this field.

1.6. Outline

This article consists of five parts in total and starts with the introduction of this paper, followed by the used research methodologies. The results and analyses are then divided into five sections so that readers can understand the logical hierarchy of this part more clearly. Research topics, current research gaps and future research directions in this field are also proposed. Finally, a conclusion is drawn.

By systematically reviewing and summarising the emerging technologies used in the existing MPC, this literature review can provide advanced knowledge for the EAT discipline in the MPC field and identify the general research direction of the discipline in the future, thus helping the researchers to a great extent.

2. Research Methodologies

This research is conducted as a systematic review, which is a repeatable process that documents some existing EAT research related to the MPC thematic area or specific research issues. To meet the objectivity and systematisation of the review, this research is mainly conducted with the following methods.

2.1. Selection of Mainstream Academic Papers

The review methods of previous studies [6,37,43] provide a valuable reference for the selection of academic papers targeted in the EAT research field related to MPC. In the MPC field, Li et al. [6] searched for related terms, using Scopus to identify the most published journals and selected articles that contain these terms in the title/abstract/keyword for review. On the basis of this method, the authors of the present study used the Web of Science (WoS), Scopus, ScienceDirect and Emerald search engines, which are frequently used by most researchers, especially new ones, to identify major papers on EAT research related to MPC that were published between 2009 and 2020. The main reasons for choosing WoS, Scopus, ScienceDirect and Emerald as the retrieval engines are: (1) articles cover a wide range and subject types are rich; (2) more perfect functions (such as citation analysis

and retrieval result analysis); and (3) to obtain more comprehensive and valuable related articles. On the basis of research experience, keyword retrieval is widely regarded as an important method for identifying as many relevant articles as possible. Above all, by searching the two main keywords—'emerging advanced technologies (EAT)' and 'prefabrication construction'—only three articles were found. The reason for this problem is that EAT covers a wide range, and few people have studied this subject in MPC. To facilitate the research and gain a broad perspective, the authors retrieved the term 'prefabricated construction', obtaining 135 retrieval records. The authors also searched for certain keywords, including BIM, Internet of Things, Blockchain, RFID, point cloud, 3D printing, prefabrication, prefabricated building, modular construction, industrialised construction, industrialised building, industrialisation, precast concrete and digital intelligent construction, thereby supplementing a certain amount of literature. For storing information, such as the author, title, source publication, year of publication and abstract of all articles, the bibliographic management tool Endnote was used to save search results from the database and remove duplicates. However, although many articles could be collected in Endnote by using this method, a certain number of unwanted and irrelevant articles still appear in Endnote's literature list inevitably. 'The purpose of setting up the criteria of inclusion and exclusion is to make sure that we only use research that is relevant to our study' [41]. Accordingly, the authors of the present study established the criteria of exclusion for screening articles, that is, the titles and abstracts of articles. If the title of an article is irrelevant to the study, then the abstract of the article is reviewed, and if both criteria are irrelevant to the study, then the article is excluded. Ultimately, after the screening, the total number of publications obtained was 526. In addition to considering the title/abstract/keyword of the article, the key article is analysed and summarised in full text for review in this research, thereby improving the rigour of the review and reducing the bias of the researchers. The workflow of the literature search for this study is shown in Figure 1.

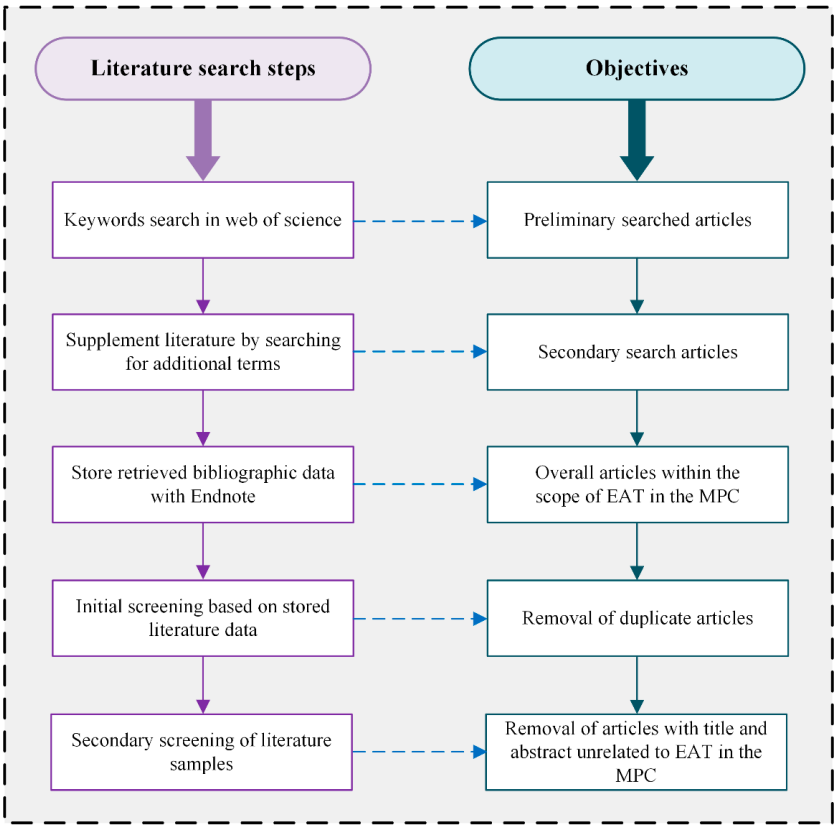

Figure 1. Workflow of the literature search for the present study (adapted from Jin et al. [44]).

2.2. Comprehensive Data Analysis of Literature Samples

To gain an in-depth understanding of the major research points and to analyse future research directions and trends in this domain, the overview of the literature sample, the co-occurrence of keywords, co-authorship analysis, countries actively engaged in EAT research related to MPC, and institutions active in EAT research related to MPC were quantitatively assessed and analysed by adopting the approach of Li et al. [6] and Jin et al. [44]. In the first section, the bibliometric analysis method was mainly used to collect data for quantitative analysis. For the remaining four sections, VOSviewer was used to perform scientific mapping and to export data for analysis. The bibliometric analysis method is mainly to obtain the required publications by searching the keywords and then to conduct classification and analysis. Given that scientific mapping with the VOSviewer tool for analysis was the most used method in this article, a brief overview of the tool is provided as follows.

To reduce the workload of researchers and make the research work lightweight, a structural visual text analysis tool, VOSviewer, was applied to generate the visual map. Distance-based network maps can be created through VOSviewer, where the distance between nodes indicates the degree of intimacy between nodes. The literature data downloaded from certain databases (e.g., WoS) can be transferred to VOSviewer to generate the network among publications [44]. In addition, researchers can flexibly adjust the parameters of the generated network (e.g., attraction and repulsion) to meet the actual needs of their research topics. As an important index to measure the influence of academic works or publications, citations are often used to identify the most influential research in a certain field. The authors of the present study first used Endnote to export the literature collected after the second screening in the author–date format to obtain citation data, and then used VOSviewer to create a map to analyse the text data of the exported citation data.

These methods can determine the current status of EAT research in the MPC field and which countries or regions, institutions and authors are the main contributors in this field, thereby assisting subsequent researchers.

3. Results and Analyses

On the basis of the above narrative and analysis, this section is divided into five sections. The basic framework of this section is illustrated in Figure 2.

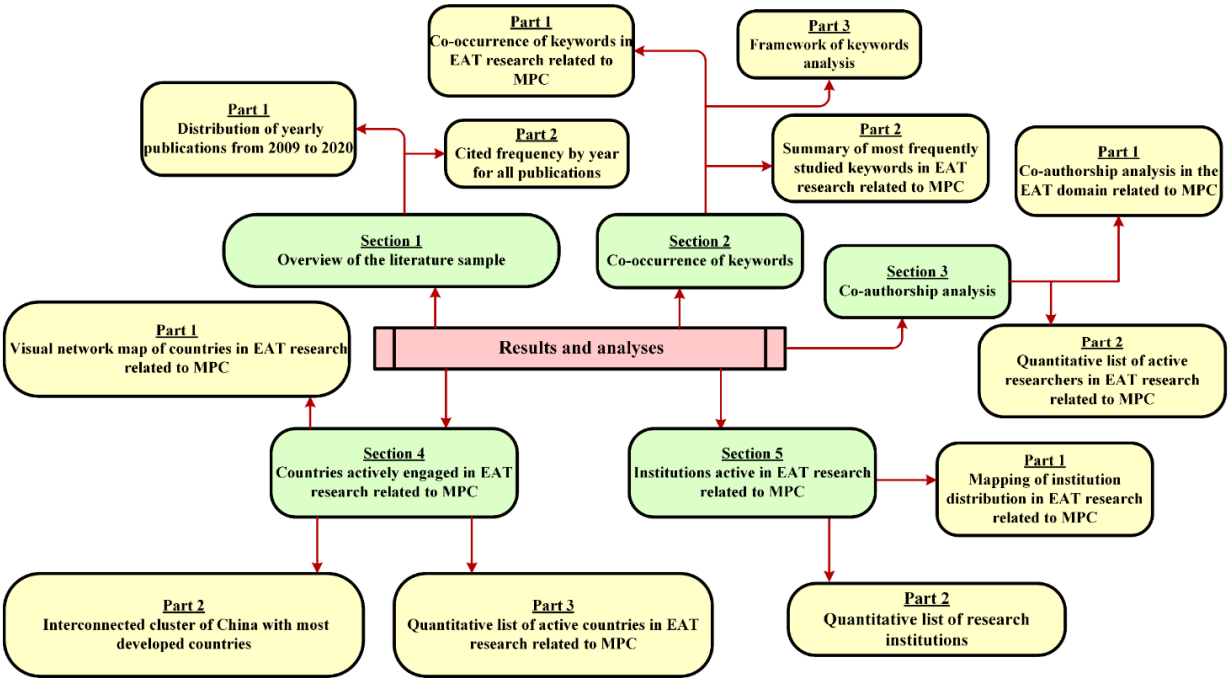

Figure 2. Framework of results and analyses.

3.1. Overview of the Literature Sample

This section mainly studies and analyses the annual publication distribution of EAT research in the MPC field from 2009 to 2020 and cited frequency by year for all publication samples.

The distribution of publications per year during the period from 2009 to 2020 is shown in Figure 3.

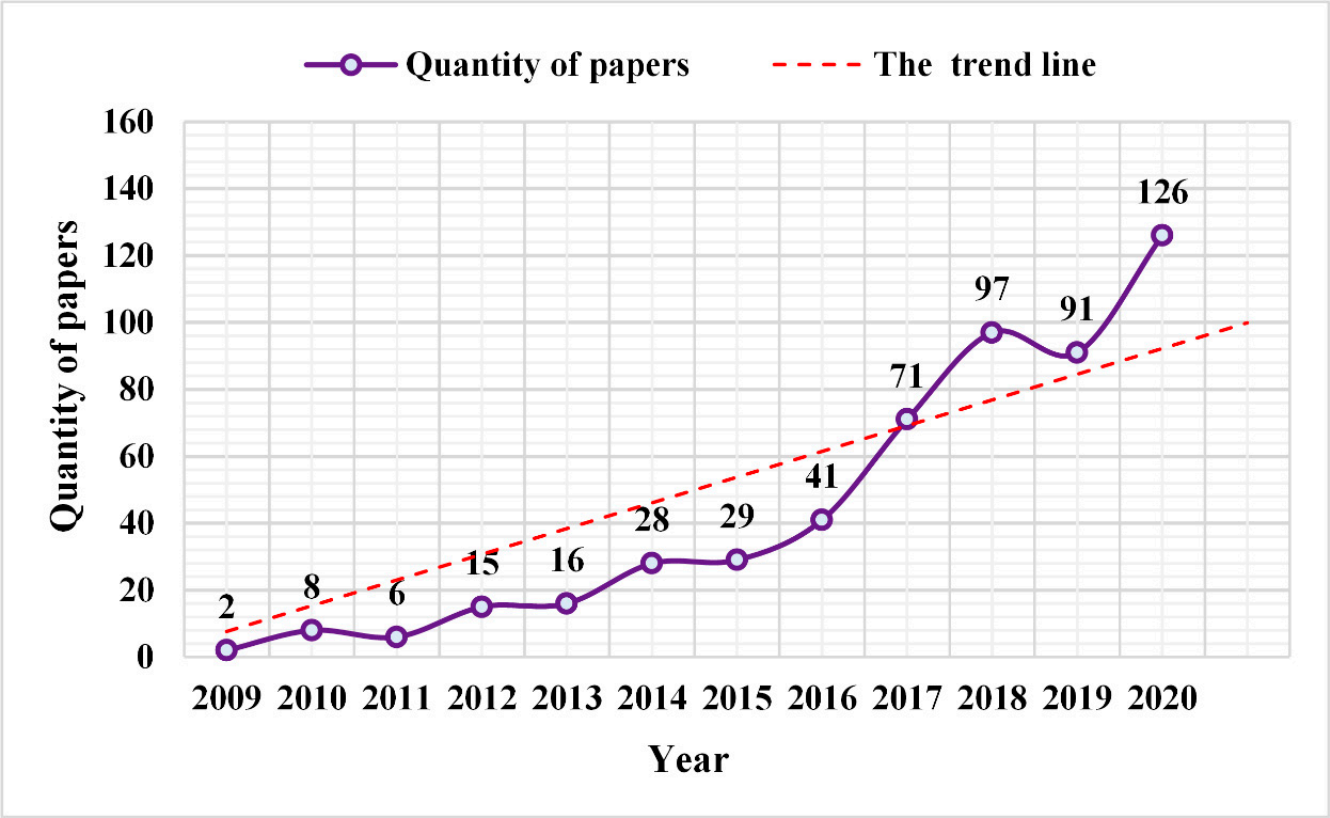

Figure 3. Distribution of yearly publications from 2009 to 2020.

Figure 3 illustrates the overall growth trend of publications from 2009 to 2020. According to the figure, the past decade can be further divided into three periods: (1) From 2009 to 2013, the number of EAT publications in the MPC field was still low with less than 20 journal articles published annually; (2) From 2014 to 2016, the number of publications significantly increased compared with previous years with more than 20 papers; (3) The yearly number of academic publications has been soaring to 71 or more since 2017. As a consequence, based on this current trend, the research output of EAT in the MPC field is expected to continuously grow in the next few years. After this analysis, all publication samples were quantitatively studied and analysed for annual cited frequency. Figure 4 is as follows.

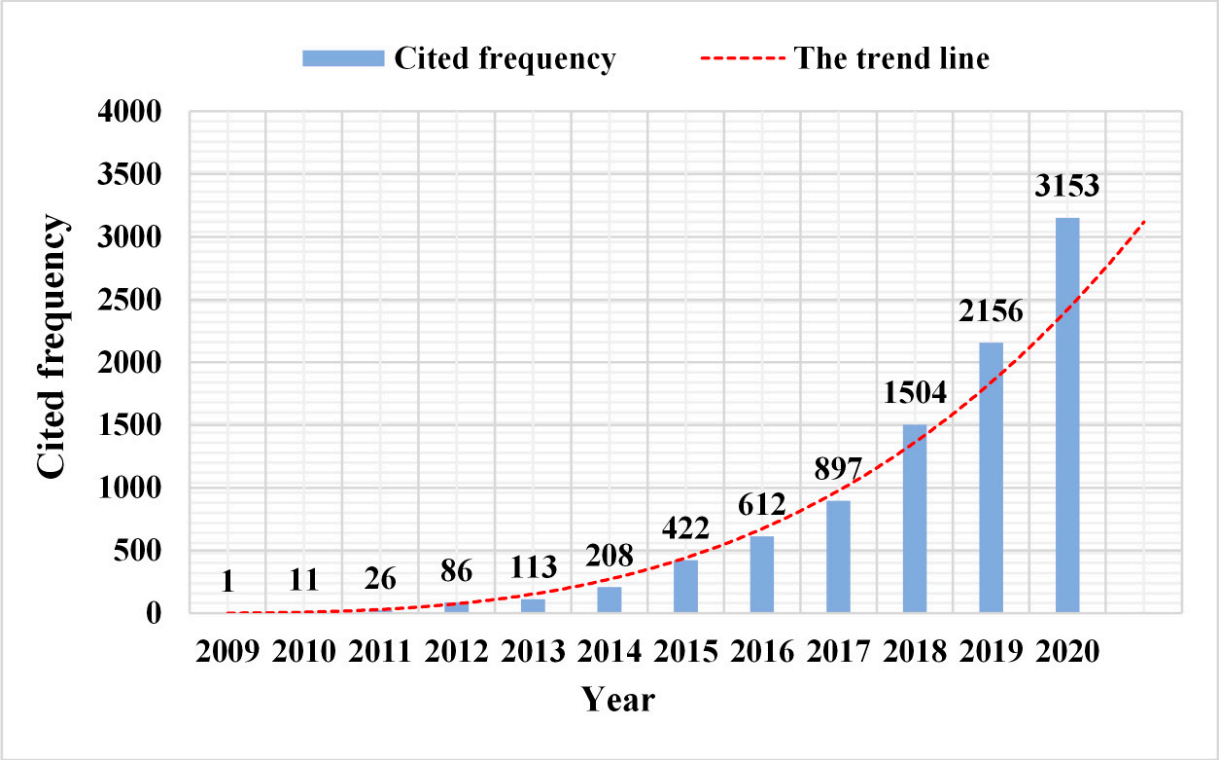

Figure 4. Cited frequency by year for all publications.

Figure 4 highlights the general increasing trend of cited frequency by year for all publications. The period from 2009 to 2020 can be further divided into three periods: (1) From 2009 to 2012, the cited frequency by year of EAT in the MPC field remained low without exceeding 100; (2) From 2013 to 2017, the cited frequency by year significantly increased to a range from 113 to 897 annually, but still below 1000; (3) Since 2018, the yearly cited frequency has skyrocketed to 1504 or more. Therefore, with this current trend, the cited frequency by year in EAT related to MPC is expected to continuously grow in subsequent years.

3.2. Co-Occurrence of Keywords

Generally, keywords can clearly and intuitively present the main content of existing research and reveal the research topic of a specific field [44]. In this study, the co-occurrence network analysis of key words is carried out to reveal the relationship between research topics. As regards the analysis type of co-occurrence, 'author keywords' and 'fractional counting' were used for analysis, and the minimum number of occurrences of a keyword was set to four. In the output, initially, 65 out of 1747 keywords met the threshold. Within these 65 keywords, some keywords with semantically consistent meanings were combined, such as 'Off-site construction' and 'OSC', 'BIM' and 'Building Information Modelling' and 'Construction' and 'Building'. A total of 43 main keywords are shortlisted and visualised in Figure 5.

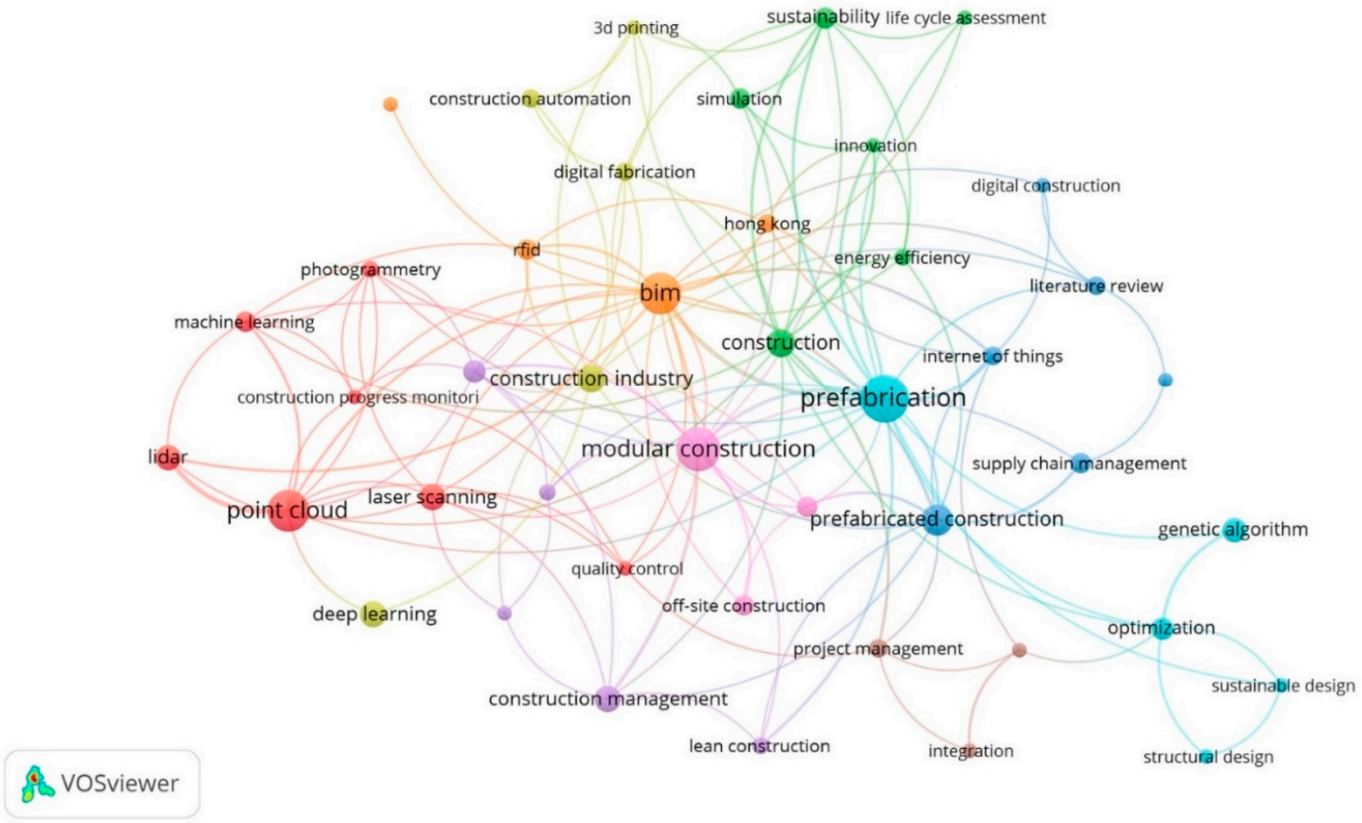

Figure 5. Co-occurrence of keywords in EAT research related to MPC.

Figure 5 illustrates nine clusters in total, and prefabrication was the most commonly studied keyword. Other keywords that most frequently co-occurred with prefabrication included modular construction, BIM, construction, point cloud, sustainability, innovation, lean construction, IoT and genetic algorithm. The clusters and connecting lines between keyword nodes in Figure 5 show these main research areas in EAT related to MPC: (1) EAT research in MPC is often linked to BIM [8,24], which is in the same cluster with RFID [10–12,22,45–50] and energy saving [51]; (2) EAT in MPC does not simply apply to modular construction [52,53] but involves off-site construction [54]; (3) EAT in MPC is also widely used in prefabricated construction for construction project management [55], supply chain management [56] and digital construction using IoT [57], and literature review is one of the main research methods used in investigating EAT related to MPC. Some scholars have also studied the status quo of EAT research in the MPC field through the form of literature review [58,59]; (4) Point cloud [60], laser scanning using lidar and photogrammetry [61,62] and machine learning [63] are used in the construction progress monitoring [64] and quality control [65] of prefabricated construction; (5) Genetic algorithm is also used to optimise structural design and sustainable design in prefabrication [66,67]; (6) 3D printing and deep learning are also gradually applied in the MPC field for digital construction, promoting the transformation of the traditional construction industry to construction automation [58,68,69]; (7) Simulation is also often used in the MPC field for life cycle assessment to improve energy efficiency and sustainability, better guide construction and further promote innovation in the technical field [70–72]; (8) The concepts of automation and lean construction are increasingly integrated into construction management for better project planning and design and virtual design and construction [73,74]; (9) Some advanced methods and technologies have also been correspondingly applied and integrated to develop an intelligent decision-making system in project management [75,76]. In addition, several countries or regions have been also showing a high degree of activity in researching EAT related to MPC, including China. To analyse the research strength of keywords from a

quantitative perspective, the quantitative measurements of keywords are summarised in Table 1.

Table 1. Summary of most frequently studied keywords in EAT research related to MPC.

No.	Keyword	Occurrence	Total Link Strength
1	Prefabrication	41	30
2	Modular Construction	32	20
3	BIM	30	35
4	Point Cloud	30	16
5	Prefabricated Construction	17	14
6	Construction Industry	14	10
7	Laser Scanning	12	9
8	Construction Management	12	8
9	Deep Learning	12	2
10	Lidar	11	9
11	Genetic Algorithm	10	3
12	Automation	9	11
13	Optimisation	9	6
14	Sustainability	8	8
15	Machine Learning	7	7
16	China	7	7
17	RFID	7	5
18	Simulation	7	4
19	Supply Chain Management	7	4
20	Off-site Construction	7	4
21	Hong Kong	6	7
22	Digital Fabrication	6	6
23	Literature Review	6	5
24	Project Management	6	4
25	Construction Automation	6	3
26	Photogrammetry	5	7
27	Lean Construction	5	5
28	Energy Efficiency	5	4
29	Project Planning and Design	5	4
30	3D Printing	4	6
31	Construction Progress Monitoring	4	6
32	Quality Control	4	6
33	Decision Making	4	5
34	Innovation	4	5
35	Virtual Design and Construction	4	4
36	Digital Construction	4	3
37	Integration	4	3
38	Life Cycle Assessment	4	3
39	Sustainable Design	4	3
40	Structural Design	4	2
41	Construction Project Management	4	2
42	Energy Saving	4	1
43	Safety Management	4	0

Given that keywords can reflect the core content of publications to a certain extent, the key research topics related to EAT research in the MPC field will be effectively identified through the analysis of keywords. As presented in Table 1, apart from prefabrication, other keywords most commonly mentioned in EAT include modular construction, BIM, point cloud, prefabricated construction, construction industry, laser scanning, construction management and deep learning, with 32, 30, 30, 17, 14, 12, 12 and 12 occurrences, respectively. Multiple studies focus on the movement of EAT in Hong Kong, addressing various issues, such as information sharing and supply chain risk [18], visualisation and traceability of construction progress [12] and the demand for low energy consumption [13]. However, only relying on the cluster analysis and summative quantitative analysis of keywords

cannot clearly and effectively analyse the current research status. Therefore, a framework of keyword analysis has been constructed to further explore the internal logic of keywords. The framework diagram of keyword analysis is shown in Figure 6.

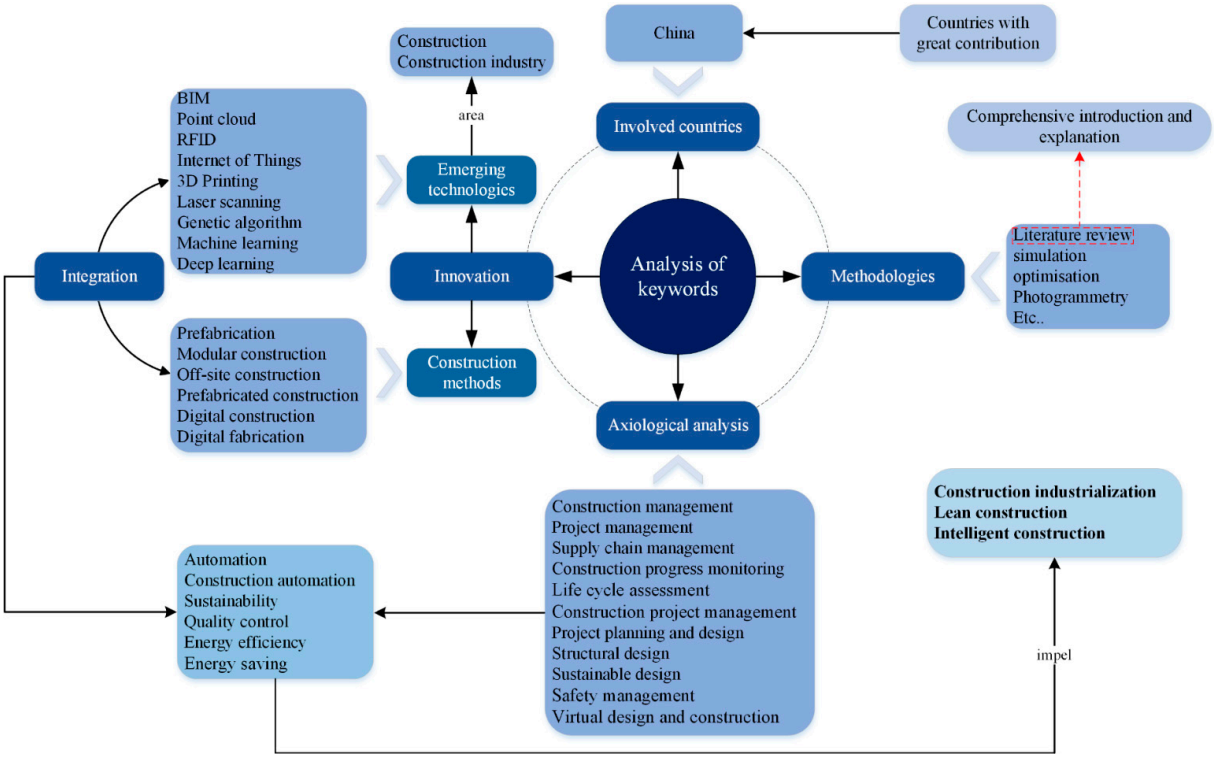

Figure 6. Framework of keywords analysis.

As shown in Figure 6, keywords have been classified from the four perspectives of innovation, involved countries, methodologies and axiological analysis.

(1) From the perspective of innovation, two new research trends have developed in the current construction field: emerging technologies and construction methods. In emerging technologies, innovations such as BIM, point cloud, RFID, IoT, 3D printing, laser scanning, deep learning, genetic algorithm and machine learning can promote the development of the construction industry. Such technologies have also attracted widespread attention and research from an increasing number of peer researchers in the construction field. In terms of construction methods, prefabrication, modular construction, off-site construction, prefabricated construction, digital construction and digital fabrication have become the research hotspots of current peer scholars. With the gradual application of emerging technologies to these fields, modular integrated construction using industrial production methods, intelligent off-site construction and digital prefabrication will become the new directions for the development of traditional prefabricated construction, promoting traditional construction to lean construction.

(2) In terms of involved countries, scientific research institutions and researchers in China have greatly contributed to EAT research in MPC, which is closely related to China's rapid economic development and strong construction demand.

(3) In terms of methodologies, the publications of EAT research in the MPC field are mainly in the form of literature review. In many empirical research articles on emerging technologies, simulation [77] and optimisation often focus on the performance evaluation of emerging technologies in the MPC field. In addition, photogrammetry is often integrated with technologies, such as BIM, machine learning and laser scanning, to achieve research goals. For example, Moon et al. [60] used drones and laser

scanning to take photogrammetry of the three-dimensional shape of buildings and obtain point cloud data. Braun et al. [64] combined reverse photogrammetry and BIM to automatically mark construction site images and used machine learning for more reliable data monitoring.

(4) From the perspective of axiological analysis, construction management, project management and supply chain management have been widely studied in construction project management. Such efforts include the implementation of construction progress monitoring based on BIM visualisation and cloud computing [78], Scan-vs-BIM [79], project planning and design by using BIM 4D modelling [80], quality control of prefabricated components by using laser scanning and BIM [65], structural design [81] and sustainable design using BIM technology [82]. With the integration of emerging technologies and construction methods, construction management, project management and supply chain management will greatly advance automation and sustainability, strengthen quality control and improve energy efficiency, promoting the development of prefabricated construction towards construction industrialisation, lean construction and intelligent construction.

Many advanced technologies have emerged in prefabricated construction. However, the lack of investigation into EAT related to MPC by current researchers leads to a large number of knowledge gaps in this field, also indirectly affecting the development of prefabricated construction, providing a new research direction for future researchers.

3.3. Co-Authorship Analysis

To gain an in-depth understanding of existing collaborations among researchers in EAT research related to MPC, a co-authorship analysis was conducted by using the VOSviewer tool. In this study, the counting method adopted the method of full counting; publications with a large number of authors were ignored and the maximum number of authors per publication was set to 25. Furthermore, the minimum numbers of publications and citations were respectively set to four and ten. A total of 50 of the 1291 authors were identified. However, some of the 50 items in the network were not connected to each other, and the largest set of connected items consisted of 28 items. Thus, the final network was generated by 28 items. Finally, after the visual network was generated, the two parameters (attraction and repulsion) under the layout were respectively set to 2 and −2 in the analysis interface for the convenience of display and analysis. Figure 7 shows some major research collaborations between authors in the EAT domain related to MPC.

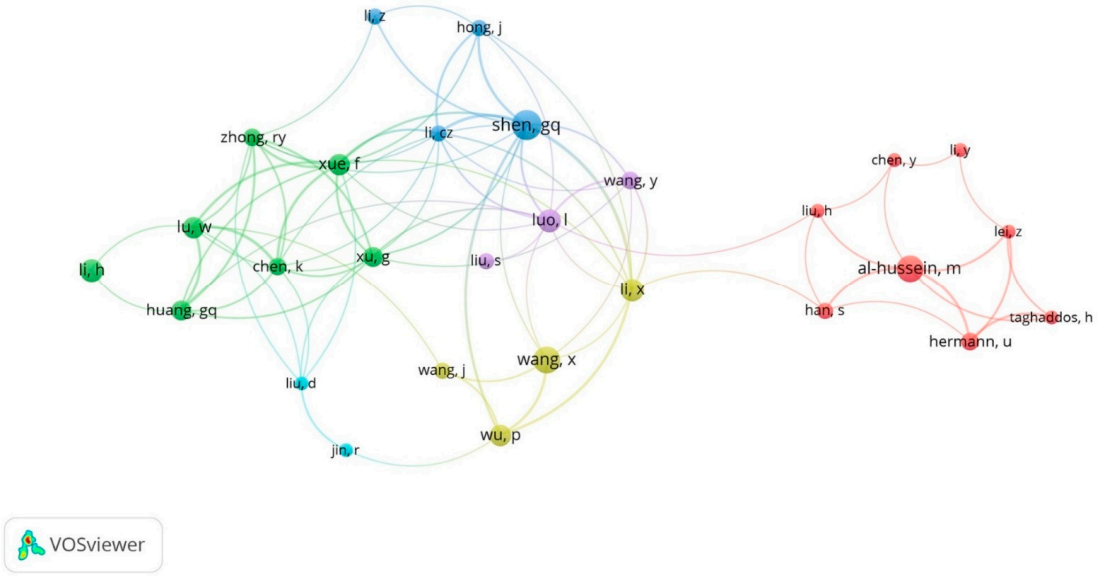

Figure 7. Co-authorship analysis in the EAT domain related to MPC.

As shown in Figure 7, some authors and clusters were productive and collaborative from 2009 to 2020. A total of six clusters were observed: the group consisting of Shen G.Q., Hong J., Li Z. and Li C.Z.; the cluster of Huang G.Q., Xue F., Chen K., Lu W., Li H., Xu G. and Zhong R.Y; the cluster of Wang X., Wu P., Li X. and Wang J.; the cluster of Al-Hussein M., Hermann U., Taghaddos H., Chen Y., Han S., Lei Z., Li Y. and Liu H.; the research cluster of Luo L., Wang Y. and Liu S. and the collaboration of Jin L. and Liu D. The quantitative summary of authors is shown in Table 2.

Table 2. Quantitative list of active researchers in EAT research related to MPC.

No.	Author	Total Link Strength	Number of Articles	Total Citations	Average Citations
1	Chen K.	18	6	279	46.50
2	Hong J.	12	5	247	49.40
3	Huang G.Q.	15	7	217	31
4	Li C.Z.	19	5	85	17
5	Li H.	2	9	30	3.33
6	Li X.	19	9	94	10.44
7	Li Z.	4	5	174	34.80
8	Liu D.	7	4	109	27.25
9	Liu H.	5	4	314	78.50
10	Liu S.	1	5	70	14.00
11	Lu W.	19	8	252	31.50
12	Luo L.	17	9	21	2.33
13	Shen G.Q.	34	13	350	26.92
14	Taghaddos H.	8	4	62	15.50
15	Wang J.	5	5	186	37.20
16	Wang X.	10	11	241	21.91
17	Wang Y.	10	6	214	35.67
18	Wu P.	15	8	248	31
19	Xu G.	18	7	269	38.43
20	Xue F.	28	8	183	22.88
21	Zhong R.Y.	18	6	48	8.00
22	Chen Y.	3	4	152	38.00
23	Al-Hussein M.	15	11	175	15.91
24	Han S.	6	5	195	39.00
25	Hermann U.	12	6	84	14.00
26	Jin R.	3	4	46	11.50
27	Lei Z.	9	4	241	60.25
28	Li Y.	2	4	243	60.75

A total of 28 productive authors are listed in Table 2. As a result, no significant correlation was found among the number of published papers and total citations. The correlation analysis showed that the number of papers published by authors is not the same as the authors' contribution to the field of EAT research related to MPC (i.e., no significant linear correlation was observed between the two indicators), which is measured by total link strength, total citation and average citation per paper. Most productive authors in the decade from 2009 to 2020 are Shen G.Q., Wang X., Al-Hussein M., Li H., Li X., Luo L., Lu W., Wu P. and Xue F., who have published 13, 11 11, 9, 9, 9, 8, 8 and 8 articles, respectively. These nine scholars have made significant contributions to EAT research in MPC. Among them, most of the publications published by Xue F. focus on the application of IoT, RFID and BIM. These studies have achieved numerous application effects. These effects include, but are not limited to, realising the seamless integration and synchronisation of the logistics echelon of prefabricated components [83], designing an IoT-enabled platform to facilitate managers to monitor construction progress and approximate cost information in real time [12] and developing an RFID-enabled BIM platform to deal with schedule factors in prefabricated house construction, reduce schedule risks and improve the schedule performance of prefabricated house construction [47]. The research of Li X., Wu P. and Shen G.Q. focuses on the application of information technologies and lean construction concepts to prefabricated housing production (PHP), and they have achieved some commendable achievements, such as developing a hands-on learning tool, namely, the advanced simulation game called RBL-PHP, which provides appropriate training or teaching methods to help practitioners in the PHP industry use

innovative information technologies such as lean and BIM [48]; proposing a conceptual framework of the integration of BIM and PHP consisting of three pillars, namely, Smart BIM Platform, Smart Work Packages and Smart PHP Objects to improve the efficiency and collaboration of the decision-making system in PHP [84]. Wang X. made certain research contributions in BIM and 3D printing in collaboration with Li X. and Wu P., such as summarising the research status quo of the BIM knowledge field [37] and analysing the application limitations and benefits of 3D printing in the construction industry [68]. Lu W. and Huang G.Q. studied the scenarios, methods and advantages of the application of RFID technology in construction project management, encouraging subsequent researchers to adopt RFID widely to improve the existing MPC practices [50]. The research of Al-Hussein M. focuses on the study of 3D visualisation systems to facilitate the rapid design of workplaces in modular construction and the application of BIM technology in the sustainable design of prefabricated components [82,85]. The research of Li H. focuses on the intelligent hoisting of automotive robots and explores the possibility of applying it to the field of prefabricated construction [86]. Luo L. focuses on the application of IoT technology in the field of prefabricated construction and the management of supply chain risks in prefabricated building projects [56,87,88]. In addition, the value of the total link strength of an author is related to the numbers of co-authors and their co-publications, potentially greatly indicating the collaborative contribution between the author and the co-authors. In Table 2, 16 out of the total 28 authors have a total link strength of ten or more, and a rough linear correlation exists between the total link strength and the number of articles published by the author. These scholars have made major contributions to the EAT research in the MPC field that can greatly help subsequent researchers to deepen their understanding of this field.

3.4. Countries Actively Engaged in EAT Research Related to MPC

To explore the countries in which EAT research in MPC is usually conducted, a knowledge network visualisation analysis was conducted for the countries in which the publication authors are located. The minimum numbers of publications and citations of a country were respectively input as four and ten, resulting in 23 out of the total 58 selected countries. Figure 8 visualises these research-active countries in EAT research related to MPC.

Figure 8 illustrates that scholars from countries with geographically close and strong economic strength and great regional influence are more likely to influence each other or cite each other's articles. A total of six clusters, including scholars from the group consisting of China (the world's second-largest economy), New Zealand, Singapore and Portugal; those from the cluster of Australia, England and Italy; the cluster of the Netherlands, Brazil, Finland, Japan, Scotland, Spain and Ireland; the cluster of Canada and Iran; the cluster of Germany, South Korea, Israel and India and the cluster of USA, Sweden and Switzerland. Developed and developing countries such as Australia and China have been active in the research of EAT related to MPC. In general, most of the countries in which EAT research in MPC was conducted are developed countries. However, although China is a developing country, it has a high number of publications in the EAT research field related to MPC and is the only cluster (Figure 9 displays that the node of the People's Republic of China is the largest among the scale of visual network nodes) that has the highest correlation with most developed countries in this field, which is largely related to the Chinese open cooperation concept, the construction demand brought about by the rapid economic development and the government's vigorous promotion of prefabricated construction. The quantitative indicators of countries are shown in Table 3.

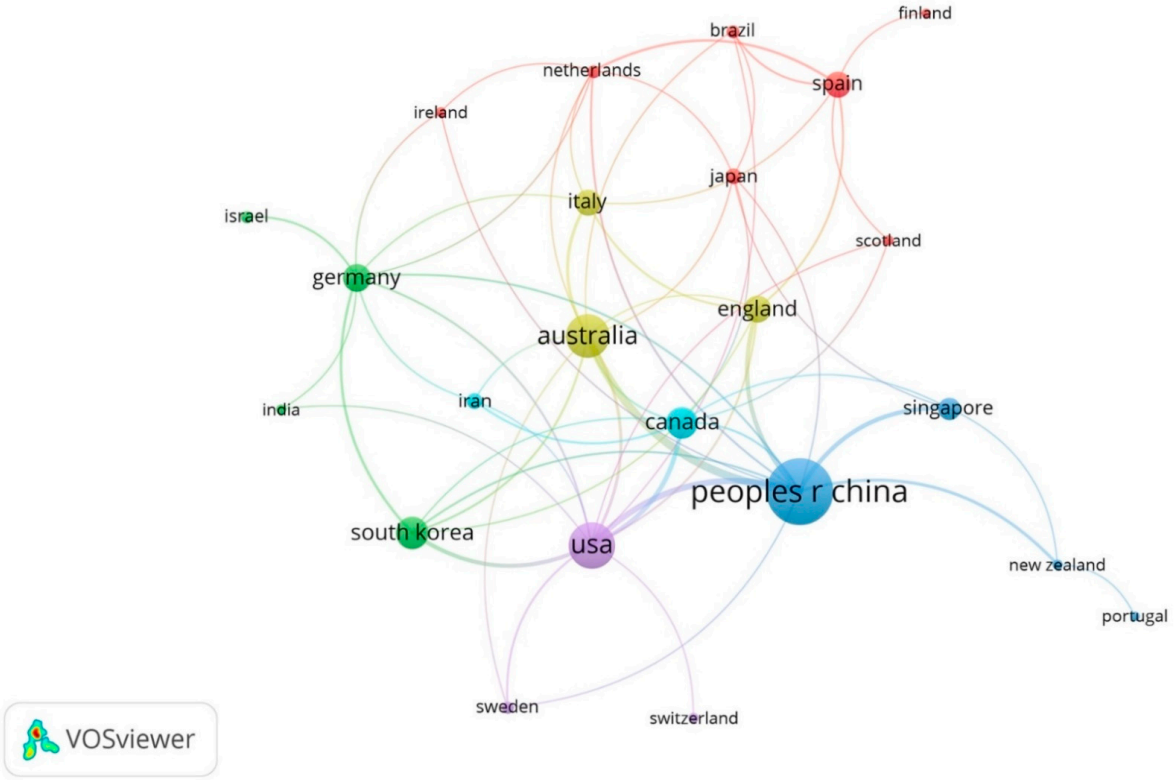

Figure 8. Visual network map of countries in EAT research related to MPC. (Note: China is the abbreviation of the People R China).

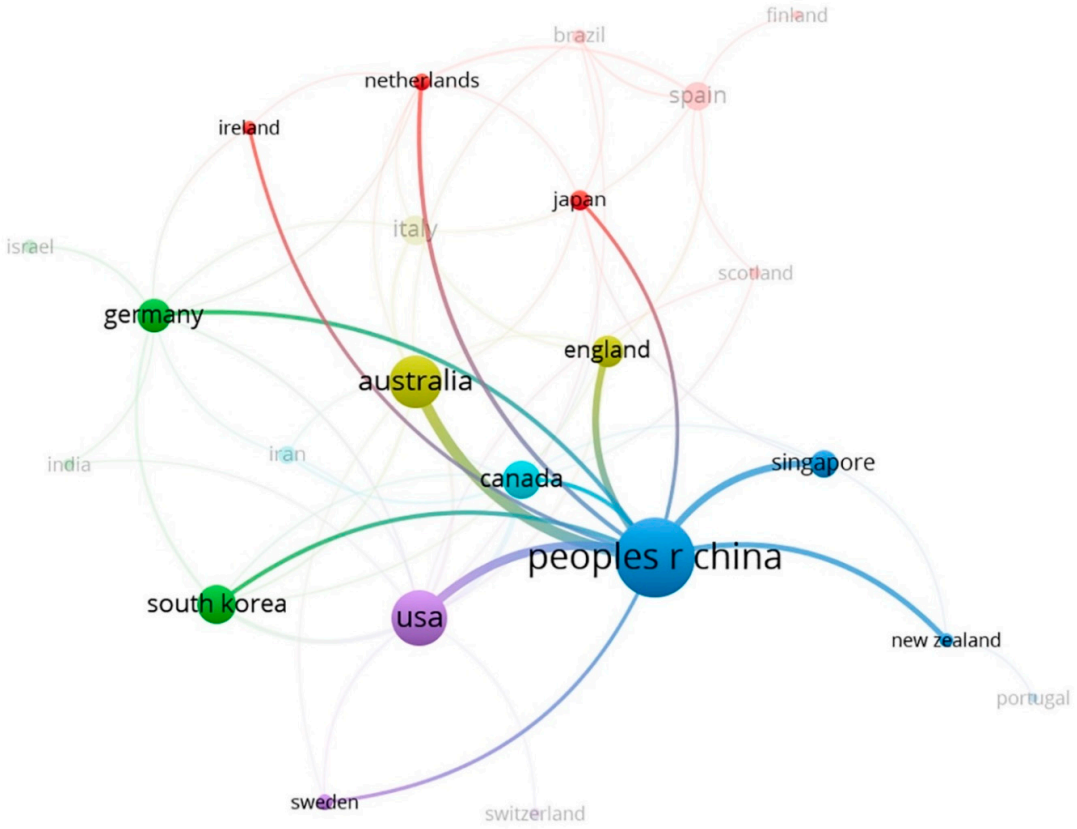

Figure 9. Interconnected cluster of China with most developed countries (Note: China is the abbreviation of the People R China).

Table 3. Quantitative list of active countries in EAT research related to MPC.

No.	Country	Total Link Strength	Quantity	Total Citation	Average Citation
1	Australia	46	69	1549	22.45
2	Brazil	5	8	114	14.25
3	Canada	19	38	897	23.61
4	England	16	28	710	25.36
5	Finland	1	4	66	16.50
6	Germany	14	30	1508	50.27
7	India	2	5	59	11.80
8	Iran	5	11	153	13.91
9	Ireland	3	5	69	13.80
10	Israel	2	7	92	13.14
11	Italy	9	27	282	10.44
12	Japan	6	11	47	4.27
13	Netherlands	10	8	92	11.50
14	New Zealand	6	5	139	27.80
15	China	75	152	2484	16.34
16	Scotland	3	5	247	49.40
17	Singapore	11	20	228	11.40
18	South Korea	16	40	668	16.70
19	Spain	10	26	442	17.00
20	Sweden	4	7	330	47.14
21	Switzerland	1	5	114	22.80
22	Portugal	1	4	108	27.00
23	USA	47	78	2618	33.56

As can be seen from Table 3, scholars from China, the USA and Australia are among the top in terms of the number of publications, ranking first, second and third, respectively. In addition, China is the country with the highest total link strength in EAT research related to MPC. In terms of influence and mutual citations, the USA, China, Germany, Australia, Canada, England and South Korea play a significant leading role in advancing the research direction of EAT in MPC. However, as a whole, China is at the core of leadership in EAT research related to MPC.

3.5. Institutions Active in EAT Research Related to MPC

EAT studies in MPC are usually conducted within the context of an organisation or institution. Therefore, institutions where the publication author is located were also discussed for their contributions to EAT research in MPC. The minimum numbers of publications and citations were respectively input as five and ten, resulting in 22 out of 482 selected institutions. Figure 10 visualises these research-active institutions in EAT research related to MPC.

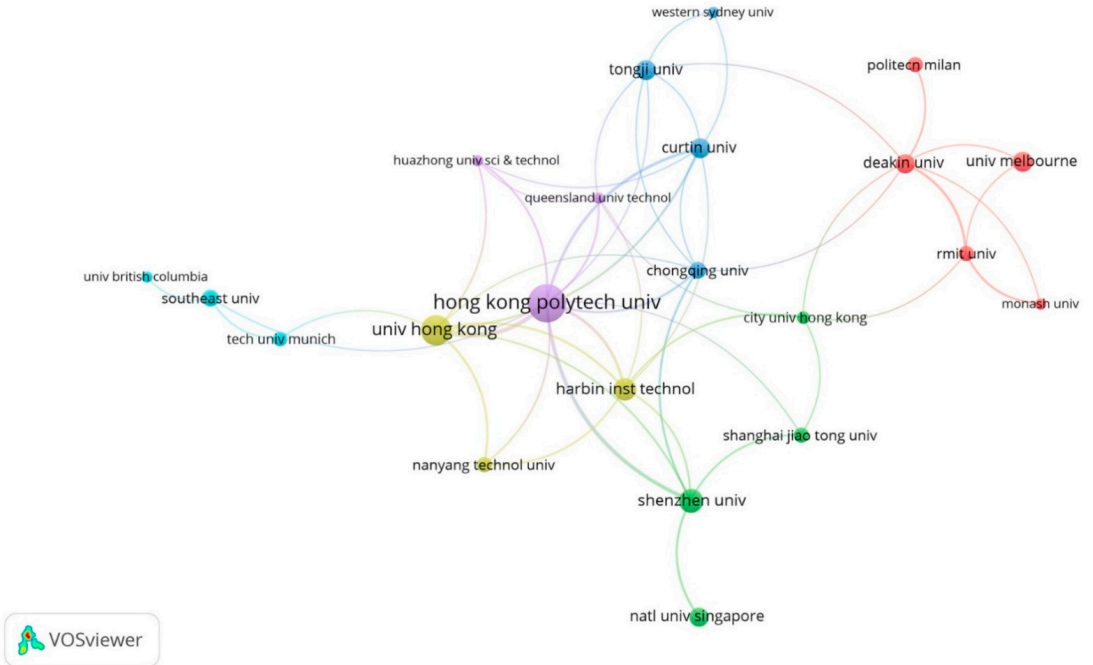

Figure 10. Mapping of institution distribution in EAT research related to MPC.

As shown in Figure 10, a total of six research clusters were found, namely, the cluster of Deakin University, Monash University, Politecn Milan (Polytechnic University of Milan), RMIT University and the University of Melbourne; the group consisting of the Harbin Institute of Technology, Nanyang Technological University and The University of Hong Kong; the cluster of Chongqing University, Curtin University, Tongji University and Western Sydney University; the cluster of City University of Hong Kong, National University of Singapore, Shenzhen University and Shanghai Jiao Tong University; the cluster of The Hong Kong Polytechnic University, Huazhong University of Science and Technology, and Queensland University of Technology and the collaboration between Southeast University, Technical University of Munich, and University of British Columbia. Furthermore, The Hong Kong Polytechnic University, The University of Hong Kong, Harbin Institute of Technology and Shenzhen University have been productive and collaborative with the greatest contribution to EAT research related to MPC. The quantitative summary of institutions is shown in Table 4.

Table 4. Quantitative list of research institutions.

No.	Institution	Country	Quantity of Papers	Total Link Strength	Total Citation	Average Citation
1	Chongqing University	China	9	10	258	28.67
2	City University of Hong Kong	Hong Kong (China)	6	6	107	17.83
3	Curtin University	Australia	12	13	424	35.33
4	Deakin University	Australia	11	11	224	20.36
5	Harbin Institute of Technology	China	14	16	329	23.50
6	The Hong Kong Polytechnic University	Hong Kong (China)	31	43	1195	38.55
7	Monash University	Australia	5	4	89	17.80
8	Nanyang Technology University	Singapore	8	7	124	15.50
9	National University of Singapore	Singapore	11	3	95	8.64
10	Politecn Milan (Polytechnic University of Milan)	Italy	8	2	97	12.13
11	RMIT University	Australia	8	9	266	33.25
12	Shanghai Jiaotong University	China	8	4	123	15.38
13	Shenzhen University	China	15	20	352	23.47
14	Tongji University	China	12	6	215	17.92
15	The University of Hong Kong	Hong Kong (China)	22	26	721	32.77
16	The University of Melbourne	Australia	12	2	412	34.33
17	Western Sydney University	Australia	5	2	109	21.80
18	Huazhong University of Science and Technology	China	5	7	69	13.80
19	Queensland University of Technology	Australia	5	7	130	26.00
20	Southeast University	China	9	3	16	1.78
21	Technical University of Munich	Germany	7	2	100	14.29
22	University of British Columbia	England	5	1	143	28.60

In Table 4, a total of 22 productive institutions are listed. China (including Hong Kong) has the largest number of research institutions in EAT research related to MPC, occupying ten seats, followed by Australia with seven seats. In terms of the number of publications, The Hong Kong Polytechnic University tops the list with 31 articles, followed by The University of Hong Kong, Shenzhen University, Harbin Institute of Technology, the University of Melbourne, Curtin University, Tongji University, Deakin University and the National University of Singapore of 22, 15, 14, 12, 12, 12, 11 and 11, respectively. As an analysis indicator in VOSviewer, the total link strength can roughly reflect the degree of importance of a particular study individual. The Hong Kong Polytechnic University and the University of Hong Kong rank top in total link strength, with 43 and 26, respectively,

indicating that they are the core institutions for EAT research in MPC. In terms of influence and mutual citations, The Hong Kong Polytechnic University, The University of Hong Kong, Curtin University and The University of Melbourne have been playing a significant role in promoting EAT research related to MPC.

4. Discussions

Following the scientometric analysis of the literature sample, keywords, scholars, countries and institutions involved in EAT research related to MPC, qualitative analysis was performed to summarise the current research topics, identify the existing research gaps and provide future research in this field with exploratory suggestions.

4.1. Research Topics within EAT in the MPC Field

4.1.1. Prefabrication

As illustrated in Figure 5, prefabrication has been a mainstream topic of EAT related to MPC in academic research and practice. Prefabrication has been widely promoted due to its many potential benefits in construction, as follows:

(1) Factory production of prefabricated components, so that the quality of components can be better controlled and labour costs can be reduced [6,70];
(2) The characteristics of prefabricated construction determine a shorter construction period, which can greatly improve construction efficiency [70];
(3) Prefabricated components are standardized and modular for design and production, and are then transported to the construction site for assembly, which reduces various forms of waste to a certain extent [4];
(4) The factory production method of components makes the construction site produce less garbage, so it is more green and environmentally friendly;
(5) The use of thermal insulation prefabricated components makes prefabricated building more energy-efficient.

In the MPC field, the design, production, transportation and assembly of prefabricated components is a lean and rigorous process, and any mistake in any link may greatly affect the quality and efficiency of the subsequent stages. In addition, prefabricated construction also has some disadvantages, such as higher transportation costs for prefabricated components, poor structural seismic resistance, restrictions on the production of larger components, and so forth, and the existing prefabricated construction has encountered certain problems in practical applications (e.g., unreasonable design, delayed information delivery, inefficient management and lagging material supply). To promote lean construction and solve the existing problems and deficiencies of prefabricated construction, an increasing number of researchers are incorporating EAT in prefabricated construction, making prefabrication a mainstream research topic in EAT research related to MPC.

4.1.2. Modular Construction and Off-Site Construction

As a new model in the development of prefabrication construction, modular construction is assembled by many module units; each module unit is prefabricated in the factory and then transported to the construction site and assembled reliably [89,90]. Owing to the need for environmental protection and sustainable construction, modular construction is increasingly widely recognised in the construction industry. Many scholars have shown considerable interest in the research of modular construction and have achieved some research outputs. For example, Generalova et al. [53] emphasised the great advantages, prospects and practical significance of modular prefabricated units in construction applications by analysing the advanced experience of modular buildings worldwide. Considering that the traditional management methods of modular construction often lead to site-fit rework and increased project risks, Shahtaheri et al. [91] proposed a framework to optimise design dimensions and geometric variability by using a comprehensive tolerance strategy that minimises manufacturing costs and project risks. On the basis of the fact that traditional construction supply chain logistics systems cannot adapt to the needs of modular

construction applications, Hsu et al. [92] established a mathematical model to optimise the logistics process of modular construction covering three levels of operation: manufacturing, storage and assembly. Modular construction mainly has the following advantages:

(1) The modules can be flexibly combined and decomposed;
(2) The function of a single module can be debugged and upgraded as required;
(3) Each module is independent of each other, which can achieve non-interference when multiple people cooperate.

However, although modular construction has many advantages, there are also some defects in the implementation process, such as higher performance loss caused by communication between modules [89] and so forth, which has also attracted widespread attention and aroused the interest of researchers. With the gradual research, development and application of modular construction, the requirements for construction quality, cost and efficiency are increasing, prompting researchers to integrate EAT into modular construction to make up for the defects in the implementation process of the current modular construction to meet the development needs of the current construction industry, making modular construction a research hotspot in EAT research related to MPC.

As a new and sustainable construction method, off-site construction has elicited great interest from the architecture, engineering and construction industries since the beginning of the century. Similarly, in the field of academic research, off-site construction has also attracted great attention from peer researchers [54]. Many scholars have conducted in-depth studies in this field. For example, Jin et al. [44] reviewed and analysed journal articles on off-site construction from 2008 to 2018 through bibliometrics retrieval and scientometric analysis, summarised the main research topics and research gaps for off-site construction and proposed a framework for future research. Jin et al. [93] reviewed and analysed the research on the environmental performance of off-site construction facilities by using the life cycle method and bibliometric analysis. It is generally believed that off-site construction (OSC) methods, such as prefabrication and modular construction, have become promising construction methods to solve traditional on-site construction challenges, including productivity, logistics, pollution, safety, waste, quality, cost and subjectivity to the environment and weather [94]. At present, emerging technologies are increasingly being applied to off-site construction to meet the needs of construction industrialisation, intelligent construction and other construction transformation. Therefore, the research on the integration of emerging technologies and off-site construction has also become the focus of current peer researchers in the construction industry.

4.1.3. Construction Industrialisation

In fact, in the MPC field, prefabrication, modular construction, and off-site construction are essentially prefabricated construction methods, but with the development of the times and different functional complexity and scale, they are distinguished by different names. Moreover, construction industrialization takes these three construction methods as the basic carrier, and realizes the high efficiency, intensification and scientific management of the construction industry by integrating modern information technologies and advanced production management modes. Construction industrialisation has attractive characteristics (including design standardisation, factory production of components, construction mechanisation and scientific organisation and management.), and advantages (including cost and time saving, improved quality, reduced resource consumption and production waste, increased labour efficiency to meet labour shortages and providing construction workers with a healthier and safer work environment). Therefore, as a modern large-scale industrial production mode, construction industrialisation is regarded as a critical approach to upgrade the traditional construction industry [95,96]. With the increasing development of the construction industry and the continuous expansion of construction scale, the requirements for labour productivity, cost and quality, energy conservation and environmental protection, and the level and content of technology are constantly increasing [97]. The traditional extensive construction management model has been unable to meet the needs

of the current development of the construction industry, and the construction industrialisation model represented by prefabricated construction has been increasingly concerned and recognised by governments, industry experts and scholars of various countries. The model has also become the mainstream trend of the current developments of the current construction industry.

4.1.4. Technical Research and Application

With the gradual development of prefabricated construction, many problems have appeared, such as extensive construction mode, low degree of information, poor information communication and a lack of coordination and cooperation among all parties. In addition, all parties involved in the construction also put forward higher requirements for the cost, quality and efficiency management of construction projects. Therefore, in the MPC field, many researchers seek technical research and try to apply technical research results to the prefabricated construction process, becoming a new research hotspot. Therefore, the authors of this study summarised the ten focal technologies of current EAT research in the MPC field.

BIM

As one of the earliest emerging innovative technologies for research and application in the construction industry, BIM has almost become the basis for the research and development of other technologies, and some innovative technologies (e.g., RFID, IoT, point cloud) have been blended with BIM technology to some extent at present. Furthermore, Table 2 shows that, among the listed technologies, the number of occurrences and total link strength of BIM is the largest, indicating that BIM, as the most basic emerging technology in the MPC field, has been widely concerned and studied by peer researchers in academic circles. BIM is also widely considered to have become the most potential innovative technology to promote the transformation of the construction industry, especially the field of prefabricated construction, to the intelligent construction stage. On the basis of the great importance of BIM technology in prefabricated construction, a knowledge framework of BIM application benefits in the MPC field was built to deeply summarise the application value of BIM technology in the full life cycle management of prefabricated construction, as shown in Figure 11.

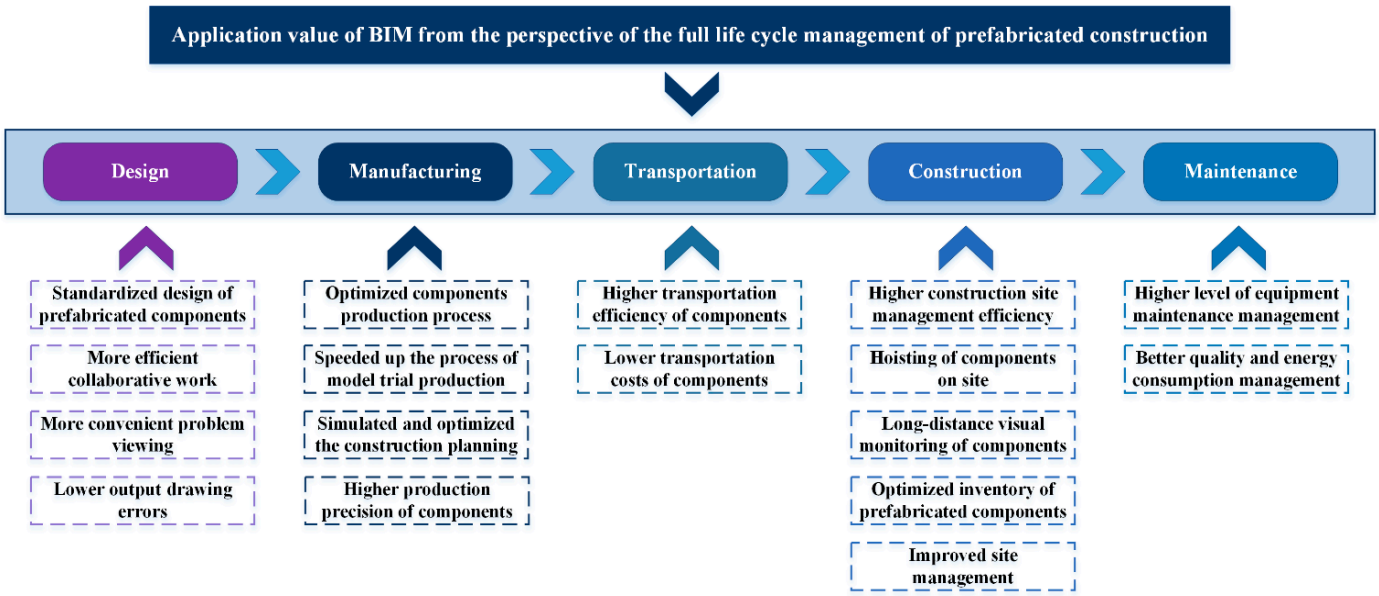

Figure 11. Framework of BIM application benefit in the MPC field.

However, despite the rapid development of BIM research, the implementation of BIM in existing prefabricated construction remains insufficient to meet the needs of existing prefabricated construction. Such an insufficiency originates from the fact that BIM technology faces some obstacles in the practical application of prefabricated construction (e.g., insufficient government support, insufficient promotion of construction units, lack of BIM technical personnel, resistance from design and construction parties, excessive implementation costs of BIM and unclear and unified BIM standards for prefabricated construction). Therefore, BIM has always been the research focus of various stakeholders in the MPC field. Given that prefabricated construction is gradually moving towards the stage of intelligent and lean construction, BIM, as one of the most widely studied and applied technologies in the EAT discipline, is increasingly becoming the core of EAT research in the MPC field.

Point Cloud and Laser Scanning

As a cutting-edge technology that can obtain the surface and spatial point data of products or components through measuring instruments, point cloud has been an increasing concern and subject for investigation. Point cloud is also generally regarded as one of the most innovative and subversive technologies in the construction industry. Furthermore, due to the improvement of accuracy and the speed of data collection and the increase in laser scanning data processing tools, laser scanning technology is becoming increasingly popular in a wide range of applications [98]. Point cloud tends to blend in with laser scanning in building model and facade profile data acquisition. Considering that traditional model building cannot capture the details of the actual components, a point cloud dataset can be customised and manually processed by intensive 3D measurement of the components construction conditions captured by a laser scanner [99]. To ensure the accuracy of the extracted feature profile of the component facade, Martinez et al. [100] proposed a new automatic data processing method for the facade laser scanner, effectively realising the segmentation and extraction of building plane features. As a data acquisition platform and measurement instrument, unmanned aerial vehicle systems are often used to detect and collect 3D geometric data of buildings for the subsequent evaluation of the generated point clouds and 3D models [101]. Point cloud and laser scanning have considerable advantages and potential application scenarios in the construction industry that are major technical achievements promoting prefabricated construction to lean, intelligent and information management and have become another research hotspot in the EAT discipline related to MPC.

RFID

RFID technology is a non-contact automatic identification technology that uses radio frequency signals to carry out non-contact two-way communication to automatically identify the target object and obtaining relevant data information. Given the advantages of improving the visibility and traceability of real-time information, RFID technology has been widely applied in various fields, such as electronic transactions, retail, logistics and supply chain management, information security and scientific research [50]. RFID is often integrated with BIM in reducing risk and improving the schedule performance of prefabricated construction [47]. With the rapid increase in the volume and scale of prefabricated construction, high requirements have been put forward for the integration and management of all links of the prefabricated components supply chain [22], prompting various stakeholders to seek and study technologies that can improve the efficiency of prefabricated construction supply chain management. As an emerging information technology, RFID can effectively solve the problems in prefabricated construction supply chain management. Thus, RFID has become an important research field in the contemporary construction industry.

IoT

IoT is a network based on the Internet, traditional telecommunications networks and other information carriers, enabling ordinary objects with independent functions to realise interconnection and intercommunication, which is often integrated with other technologies to solve the problems of lagging information and poor communication in the MPC field to effectively achieve lean construction. To track prefabricated components in real time and realise real-time interaction between components, Zhong et al. [83] proposed a decision support system (DSS) that uses IoT and cloud technology in architecture, promoting the interconnection of decision information. In the subsequent study, Zhong et al. [10] further introduced a multi-dimensional IoT-enabled BIM platform, which greatly promotes the real-time visibility and traceability of prefabricated components. Immediately afterwards, Li et al. [12] designed an IoT platform that combines IoT with BIM technology to dynamically collect data and information in real time, providing efficient decision support for the managers of various relevant stakeholders. On this basis, Zhai et al. [102] developed an IoT-enabled BIM platform, expanding the research of the DSS system into modular integrated construction. With many researchers integrating advanced technologies into the MPC field for improved prefabrication research, IoT has increasingly become a key focus in EAT research related to MPC.

3D Printing

Three-dimensional (3D) printing is a rapid prototyping technology that builds objects based on digital model files and prints layer by layer through adhesive materials. According to Wu et al. [68], cost, printing time, accuracy and available materials are the main factors that limit the application and development of the technology. Initially, the use of 3D printing is limited to manufacturing, mainly for the production of prototypes of parts with low output, small part sizes and complex designs [68]. However, with the gradual development of economic society and the technology of rapid progress, the cost and time of 3D printing have been reduced considerably; coupled with the improvement of material technology, 3D printing technology is also increasingly accepted [103]. In recent years, the use of 3D printing has been extended to construction. Especially in the field of prefabricated construction, 3D printing technology has the following outstanding advantages:

(1) Flexible design. Developers can use 3D printing to design prefabricated structural components that are difficult to produce by traditional manual practices;
(2) Mass production. The mass production of prefabricated components is carried out without affecting the customisation of prefabricated components;
(3) Reduced waste. The process of 3D printing components uses less material than the components actually need;
(4) Reduced labour. The 3D printing process of components is highly automated and intelligent, which can greatly reduce the labour required in the production of prefabricated components [104];
(5) Better economic and environmental benefits. The use of 3D printing technology can greatly reduce the production time of prefabricated components and shorten the construction period of the entire construction project, thereby saving project costs [105]. At the same time, the requirements of sustainability are met due to the characteristics of reducing material waste.

Considering its great advantages and prospects, 3D printing has been a major focus of an increasing number of peer researchers and has become a research hotspot in prefabrication construction.

Big Data and Cloud Computing

In the digital revolution, a considerable amount of data, known as big data, are continuously produced and stored. McKinsey, a world-renowned consulting and research institution, defines big data as a huge dataset that far exceeds the capabilities of traditional database software tools in the data information capture, acquisition, storage, processing and

analysis of the practical functions [106]. The construction industry has a wealth of massive data, but due to complex data and low level of information technology in the industry, 'information islands' have always been a common problem in the industry. In addition, in the MPC field, the large amount of data generated have not been effectively used. The application of big data technology can effectively integrate and transmit data in the field of prefabricated construction. In general, big data and cloud computing are intertwined. Generally, cloud computing is a service that brings together many planned resources, manages them automatically through software and makes them available quickly, with very few people involved [107]. The deep integration of big data and cloud computing can result in major advantages in the field of prefabrication construction, such as massive data storage, fast data transmission, powerful computing capacity, automatic maintenance and data security. Therefore, these two technologies have also become the research hotspots in the MPC field.

Machine Learning

As the core of artificial intelligence, the essence of machine learning is to use algorithms to parse data, learn from it and then make decisions and predictions about something in a certain field. In prefabricated construction, machine learning has been able to achieve seamless connection with 5D BIM and point cloud, helping to identify and handle changes early, optimise construction processes [64] and playing a continuous role in the full life cycle of project construction and later operations. Although practical applications of machine learning in the field of prefabricated construction are limited due to some objective restrictions, it has gradually attracted considerable interest and attention from many peer scholars due to its huge advantages and prospects.

Blockchain

As the underlying technology of cryptocurrencies such as Bitcoin, blockchain supports distributed, encrypted and secure logging of digital transactions [108]. Blockchain has many potential applications in prefabricated construction. Examples include the unique component traceability of smart contracts and documents that can be achieved by combining RFID technology [57] and tracking the payment of suppliers in the supply chain network of prefabricated construction by using integrated electronic 'proof of delivery' [57]. Through integration with innovative technologies such as BIM and big data, blockchain is gradually innovating the construction industry and has increasingly become the focus of research by many peer scholars.

4.2. Current Research Gaps

4.2.1. Systematic Review of EAT Research in the MPC Field

In the MPC discipline, although considerable research outputs and contributions in the emerging technologies have been produced by researchers, most of the existing studies are limited to analysing the application effect and feasibility of one or two technologies in prefabrication construction. Furthermore, review research of current technologies applied in the MPC field from a comprehensive perspective remain lacking. Thus, most existing research outputs are messy and scattered, making it impossible to effectively integrate. In addition, the EAT discipline has not been systematically defined and analysed by researchers, and no systematic theoretical system has been formed in this discipline. All these challenges provide new research directions for future researchers.

4.2.2. In-Depth Research on Technology Integration from the Perspective of Project Life Cycle

Although many technologies have been studied and applied to prefabricated construction, and some cases of technological integration have been investigated, these studies are based on a certain activity link in the process of prefabricated construction. For example, in the stage of assembly and construction of prefabricated components, Getuli et al. [78]

studied and proposed a visual monitoring and management system of the construction site progress model on the basis of BIM and cloud computing to improve the efficiency of real-time communication and sharing interaction of progress information during construction. However, the research on technology integration from the full life cycle process of prefabricated construction projects has not been developed at present. Therefore, the technology integration based on the full life cycle of prefabricated construction projects needs to be studied in-depth by subsequent researchers.

4.2.3. Research on the Limitations and Advantages of EAT Application

The broad prospects of EAT application in the MPC field have elicited widespread recognition and attention from the peer academic community. However, in the current MPC field, the application of emerging technologies is still subject to many restrictions, including, but not limited to, lack of knowledge of emerging technologies among construction managers [70], higher cost and lower benefit [47], imperfect policy system [109], lack of compound talents in the field of construction informatisation [2] and immature technology implementation planning [10], meaning emerging technologies have certain limitations in prefabricated construction management. Moreover, research on the limitations of EAT application in the MPC field remains lacking. Although the EAT application has some limitations, its huge application value can greatly innovate the traditional construction industry. Relevant research on the advantages of EAT in the MPC field also remains lacking.

4.2.4. Holistic Performance Evaluation on Technology Application

Based on the need to save time, resources and costs, and to protect the environment, performance appraisal is increasingly becoming a consensus theme in the construction industry. Li et al. [6] pointed out that performance evaluation has become a key research direction in the future of the MPC discipline. With the gradual research and application of advanced technologies in the MPC discipline, performance evaluation in the EAT field has also received increasing attention. However, given that the research results can vary among studies, the performance of EAT must be placed in the context of a particular country or region. For instance, Tang et al. [97], Kim et al. [33], Orlowski et al. [108] and Ji et al. [109] believed that EAT is cost-effective. However, Li et al. [110] and Qi et al. [111] revealed contrary research results, indicating that EAT leads to high costs due to various factors (e.g., high-cost prefabricated construction, the incremental cost of using advanced technologies in MPC). Furthermore, only a few studies on the performance evaluation of EAT have been made. To further analyse the benefits and obstacles of cost changes caused by the application of advanced technologies in the MPC field, the performance evaluation research of the EAT discipline still needs to be further studied.

4.3. Future Research Directions for EAT in MPC

On the basis of the above analysis, the framework that links current research areas and research themes to future directions is initiated in Figure 12.

Industry development trends and directions in the MPC field. The literature on industry development trends and directions in the MPC field mainly focuses on the construction methods that promote the adoption of EAT in prefabrication. Through a comprehensive literature research, the authors found that 'modular construction', 'off-site construction', 'construction automation', 'digital construction' and 'lean construction' were the most essential advantages of adopting EAT in prefabricated construction. As lean construction concepts and various emerging technologies are gradually integrated into modular construction and off-site construction, modular integrated construction assembled with industrialised production methods, digital off-site construction and digital prefabrication will be the important direction of future development and research. The concept of lean construction and intelligent construction is gradually recognised. Furthermore, a considerable demand for new buildings presented by lean and intelligent prefabricated buildings is observed in certain developing countries, such as China, due to rapid economic growth,

urbanisation and the development trend of construction industrialisation. Therefore, the research on the construction methods in the MPC field has become the consensus of the construction industry.

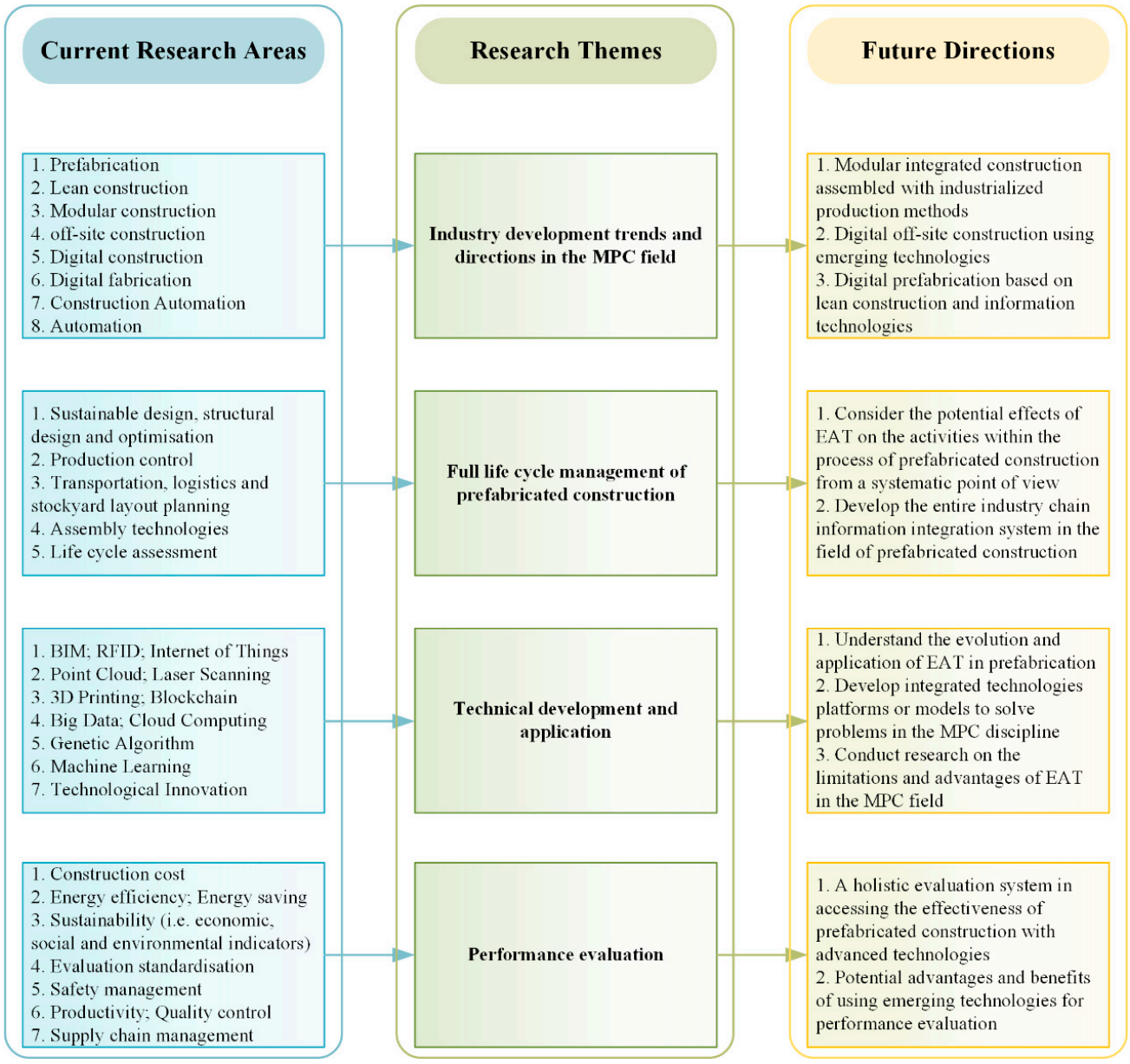

Figure 12. Framework linking the current research field with future research directions.

Full life cycle management of prefabricated construction. The monitoring and management of the precast construction process and its variables are of strategic importance when dealing with the complexity of the construction industry [6]. However, many studies on the process of prefabricated construction only focus on one link in the full life cycle of the construction project (e.g., transportation and logistics), and some MPC research focus on controlling time and cost. For example, by taking advantage of IoT and cloud technology, Xu et al. [14] focused on the transportation of prefabricated components and the control of time and cost. Given that the entire management process of precast construction is highly complex, comprehensively considering and studying in-depth the potential effects of EAT on each link of prefabricated construction from the perspective of a full life cycle is necessary. In view of the importance of information flow management in construction projects,

developing the entire industry chain information integration system is also necessary to better implement the full life cycle management of prefabricated construction.

Technical development and application. Although many technical studies have been conducted in the MPC field, the application of construction and management technologies in the field of prefabricated construction is still relatively traditional, due to the immature application of technologies and the lack of in-depth integration between technologies. Moreover, the evolution and application of many technologies lack systematic research, so that the limitations and advantages of each technology cannot be effectively and clearly distinguished, resulting in researchers not knowing which technologies can be applied to which scenarios in construction projects. This limitation hinders to some extent the technology innovation of peer researchers in the MPC field. Therefore, subsequent researchers must further understand and study the evolution and application of technologies in the field of prefabricated construction, analyse the limitations and advantages of EAT in the MPC field and further strengthen the development and research of intelligent platforms or models integrating multiple technologies in the MPC field.

Performance evaluation. In prefabricated construction, the benefits of adopting various advanced technologies have been confirmed by many researchers. Examples of these benefits are including more efficient transportation efficiency of prefabricated components; shorter construction period, fewer labour demands, better control and management of construction schedule and quality, greater potential of digitalisation, automation, informatisation and intelligent management system and safer on-site construction. However, the promotion and application of EAT in prefabricated construction can successfully be promoted only when various stakeholders gain practical benefits. Therefore, future research on EAT must investigate and build a comprehensive performance evaluation system to effectively evaluate the feasibility and rationality of various advanced technologies applied in prefabricated construction. The potential advantages and benefits of using EAT to evaluate the performance of prefabricated construction also need to be explored and analysed accordingly.

5. Conclusions

EAT applied in the MPC field remains in its early stages. However, the trend of EAT applied in the MPC field is growing rapidly. These technologies are more advanced, efficient and accurate than the traditional tools and thus greatly facilitate prefabricated construction management. EAT has been an increasing concern of peer scholars due to its high application value in the MPC field. Mature applications and practices of EAT in the MPC field require considerable time. The current application status of EAT in the MPC field is analysed and discussed through a comprehensive and systematic literature review of 526 collected papers. Based on the collected 526 sample articles, an overview of the literature sample is analysed. Then, the co-occurrence of keywords, co-authorship and activeness of countries and institutions are analysed using the structural visual texting mining tool, VOSviewer. Furthermore, the research topics and current research gaps are identified and future research directions are further proposed.

This paper presented a critical overview of the previous EAT research in the MPC discipline, helping scholars have a deep understanding of the current status of EAT research in the MPC discipline and allowing them to continue from the findings of previous studies. A large number of scholars and industry practitioners will also benefit from this study, which provides them with the results of effective technology research and application in the MPC field. Considering that no previous review research on EAT in the MPC discipline has been conducted, this study may have some deficiencies in the actual research that must be supplemented and improved by subsequent researchers.

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