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Review

A Systematic Review of Digital Technology Adoption in Off-Site Construction: Current Status and Future Direction towards Industry 4.0

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Abstract: Off-site construction (OSC) is known as an efficient construction method that could save time and cost, reduce waste of resources, and improve the overall productivity of projects. Coupled with digital technologies associated with the Industry 4.0 concept, OSC can offer a higher rate of productivity and safety. While there is a rich literature focusing on both OSC and Industry 4.0, the implementation of associated digital technologies in the OSC context has not been fully evaluated. This paper intends to evaluate the current literature of digital technology applications in OSC. Scientometric analyses and a systematic review were carried out evaluating fifteen typical digital technologies adopted by OSC projects, including building information modelling (BIM), radio frequency identification devices (RFID), global positioning systems (GPS), the Internet of Things (IoT), geographic information systems (GIS), sensors, augmented reality (AR), virtual reality (VR), photogrammetry, laser scanning, artificial intelligence (AI), 3D printing, robotics, big data, and blockchain. This review formulates a clear picture of the current practice of these digital technologies and summarizes the main area of application and limitations of each technology when utilized in OSC. The review also points out their potential and how they can be better adopted to improve OSC practice in the future.

Keywords: modular construction; prefabrication; prefabricated construction; technology adoption; BIM

1. Introduction

Off-site construction is a modern method where construction elements are produced in a controlled factory, instead of at a construction site [1,2]. In the past 20 years, off-site construction has become more and more popular. According to a survey in 2017, 90% of interviewees from a wide range of backgrounds including construction contractors, designers, manufacturers, and academic researchers, believe that the number of off-site construction projects will increase in the future [3]. Its popularity has been widely reported in China, Hong Kong, Australia, Germany, and the Netherlands [4–6].

Off-site construction may also be named as prefabricated construction, precast construction, modular construction, etc. [7–10], with subtle differences in various contexts. Some scholars define modular construction as a well-developed off-site manufacturing approach, where prefabricated modules are 85–90% completed with finishes in a factory. Off-site manufacturing also refers to prefabricated, prefinished volumetric construction (PPVC) [11–14]. In this research, these various definitions are all included and are referred to as off-site construction (OSC).

Many studies have claimed that the major advantage of OSC is that it could save up to 30–50% construction time compared to conventional construction, since construction elements or modules could be manufactured in a factory before the onsite activity starts. Therefore, site preparation and the manufacturing of construction elements can happen at the same time [5,6,15–17]. However, in the current practice of OSC, the performance of this construction method still encounters many challenges and has not yet realized its full potential in time and cost saving, as well as labour productivity. Some research has reported that the total time from design to onsite assembly could actually be longer than conventional construction [18–20]. Human labour productivity is low due to the high skill level required for on-site assembly in OSC projects [21–23]. According to an investigation in the United States (US), in reality nearly half of the prefabrication projects see less than 5% in savings in total labour hours [24]. Other studies have reported that the cost of prefabricated buildings is actually estimated to be 26.3 to 72.1% higher than that of conventional buildings [25–28]. These facts indicate that many problems need to be solved to fully realize the potential benefits of OSC. Moreover, there are many surveys conducted in the OSC industry to measure performance from different perspectives, for example, energy and environment [29–32], labour productivity [29,33], and market and social factors [29,34]. These surveys demonstrate the industry's desire to improve OSC in general.

Digital technology is regarded as the key to improve productivity in the construction industry [35,36]. According to a survey conducted in the Chinese off-site construction sub-sector, published in 2020, over 90% of respondents from construction enterprises consider the lack of advanced technology implementation as the major constraint for the development of OSC [37]. Moreover, according to a survey of contractors at a forum on OSC held in the US, 87% of 156 contractors responded that advanced technology is one of the key enablers for the use of OSC with greater accuracy and efficiency [24]. Technological advancement can provide solutions to address many current issues in construction and have come to play a significant role in construction [38]. Digital technologies have received increasing attention following the development of digitalization and automation concepts in Industry 4.0 [35,39–41]. They could be used for logistics management, near-real-time information flows, end-to-end supply chain transparency, and improvements in human interaction through the integration of digital technologies, especially labour-intensive activities [42]. Furthermore, the digital representation of design for manufacture and assembly (DFMA) practices and quality assurance can be achieved by the adoption of technologies in OSC with higher accuracy and efficiency [29]. The general adoption of digital technologies in the construction industry is slow compared to other industries, due to the lack of understanding in their identification, assessment, and selection [43–45]. This may slow down the adoption of Industry 4.0 technologies that may potentially improve current construction management issues. Successful technology adoption may facilitate the main requirement of a successful implementation of Industry 4.0. Industry 4.0 embraces the applications of the Internet of Things (IoT), robotics, 3D printing, off-site manufacturing, blockchain, cyber-physical systems, and other relevant technologies [41]. While the literature on off-site construction is growing, there is no systematic evaluation of how available digital technologies have been utilized in the construction sectors, and how these technologies can effectively enhance current OSC practices. Therefore, the aim of this study is to identify the most relevant papers on digital technology applications in the OSC context through a systematic review of the literature. Then, the identified papers are critically reviewed to analyze the limitations and the gap in the literature, which will help draft a road map for Industry 4.0 utilization. The objectives of this research are: (1) To provide a scientific mapping of the current status of digital technology utilization in OSC; (2) to identify the network links and relationships between different types of digital technologies; (3) to investigate the main research topics, current achievements, and limitations of these technologies when utilized in OSC; and (4) to point out the potential of each technology and provide guidance for its improvement and future adoption in OSC.

2. Materials and Methods

2.1. Research Process

A three-step approach is adopted to conduct a systematic literature review and analysis on how digital technologies can be utilized to overcome existing challenges in OSC. The first step is to identify specific digital technologies adopted in the construction industry from the literature searched in Scopus. Various digital technologies and relevant terminologies are identified and selected from the keywords' analysis carried out by using VOSviewer. The second step is to use the selected digital technologies/terminologies as keywords to conduct a literature search in a publication database. The third step is to carry out an in-depth review and qualitative analysis based on the database search outcome. The process for this review is illustrated in Figure 1. In this research, Scopus is used as it is one of the largest research publication databases available. Compared with other databases, it has a wide range of coverage of quality publications in the domain of construction, as well as interdisciplinary research topics [46]. The process involved in identifying specific digital technologies and the details of searching relevant papers are explained in Sections 2.2 and 2.3, respectively.

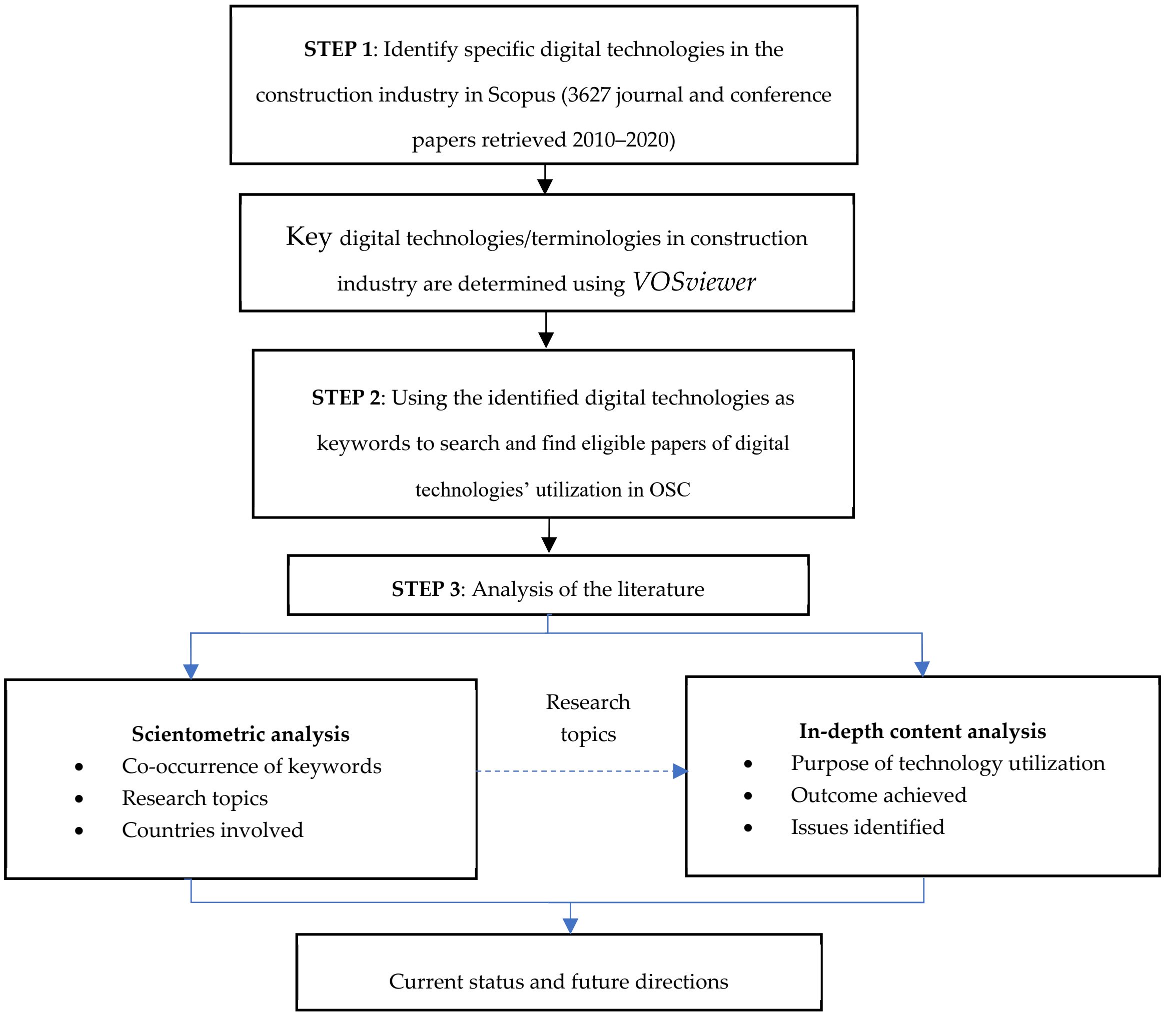

Figure 1. Systematic review process of digital technologies' adoption in off-site construction (OSC).

2.2. *Preliminary Search to Identify Keywords of Technologies*

This literature review focuses on the digital technologies used in OSC projects. Digital technology is a general term and it covers a wide range of specific techniques. To ensure the literature search covers all commonly-adopted digital technologies in the construction industry, a preliminary search was carried out to identify the specific technologies and the terminologies used in the literature. This paper reviews a variety of papers with different terminologies, and therefore, there is a need to preserve consistency throughout the current paper by defining the core technical concepts. BIM, as the core concept examined in this paper, is known as a debatable concept since it has been referred to as a solution, approach, methodology, and technology depending on the context of the investigation.

Practitioners, particularly vendors, refer to it as a solution, while academics and some stakeholders refer to it as a methodology. In this research, it is found that BIM is closely linked to many technologies. Consequently, the technology aspect of BIM is the focus of this paper. Recently, Shirowzhan et al. [47] defined technology broadly to include artefact, its relevant knowledge, and processes to solve problems. They defined technology as tools, software, hardware, electronic boards, sensors, and machines or a combination of them or any modification of them to be considered in the construction context. The definition adopted in this paper embraces BIM as a technology, and it is important to understand that BIM also refers to a process of modelling, analyzing, simulating, integrating, and visualizing building and construction information by using different tools and software [48–50].

Step 1 is to identify all the digital technologies utilized in the construction industry most recently. A preliminary search was carried out in Scopus, and in order to identify the latest digital technologies reported in the literature, the published papers are confined to the last 10 years, from 2010–2020. The papers are limited to journals and conference proceedings in English. First, "digital technology" or "digital technologies" were searched as keywords in Scopus, then the construction-related keywords were added as constraints within the results. The keyword search algorithm is:

(TITLE-ABS-KEY (digital AND technology OR digital AND technologies)) AND (construction AND industry OR construction AND project OR construction AND projects). The initial search resulted in identifying 3627 papers including journal articles and conference papers. This outcome is used for further analysis by utilizing VOSviewer, which enables the scientometric analysis including the frequency of occurrence of selected keywords. After merging abbreviations with the full terms or relevant meanings that they represent, the following technologies are identified: (1) "BIM" and "Building Information Modelling" and "Building Information Model"; (2) "IoT" and "Internet of Things"; (3) "virtual reality" and "VR"; (4) "augmented reality" and "AR"; (5) "3D printing" and "addictive manufacturing"; "3D concrete printing"; (6) "artificial intelligence" and "machine learning" and "deep learning"; (7) "laser scanning" and "3D scan"; "3D scanning"; "3D laser scanning"; "terrestrial laser scanning"; (8) "GIS" and "Geographic Information System"; (9) "GPS" and "Global Positioning System"; (10) "photogrammetry" and "video"; "drones"; and "UAV". All the technologies that appeared in the keywords are selected and visualized in Figure 2.

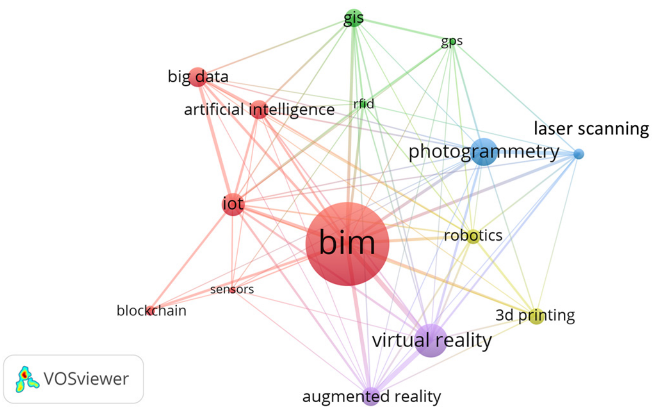

Figure 2. Visualization of keywords occurrences of digital technologies in the construction industry.

The fifteen specific digital technologies and their co-occurrences in the literature are illustrated by VOSviewer in Figure 2.

In Figure 2, the size of the circles is in proportion with the total occurrence frequency of each technology in relation to the others, while the thickness of the lines represents the link strength between two technologies [9,51]. Obviously, BIM is the most widely reported digital technology in the construction industry and it is closely linked to many other technologies. The items with the same color represent a close relationship among them and are categorized in one cluster [9,51]. An example is that virtual reality is closely linked to BIM and augmented reality [52] and laser scanning is often discussed with photogrammetry and BIM [53]. GPS, GIS, and RFID are in the same cluster, and the remaining five technologies covering sensors, IoT, AI, big data, and blockchain are grouped together, and they are all closely linked to BIM. Note that BIM technologies have been developed over the last 20 years so the total number of occurrences in the systematic review is quite high, while big data, IoT, AI, VR, and photogrammetry have been developed more recently but are quickly catching up. These fifteen digital technologies, as shown in Figure 2, are adopted as the keywords for a more detailed literature search regarding their utilization in OSC. The application of each technology is reviewed in the following sections.

2.3. Database Search for Selecting Relevant Papers

Step 2 is to identify all relevant papers on digital technology utilization in OSC. The details of the procedures involved in the database search are given in Figure 3. First, all papers related to OSC are retrieved from the Scopus database. The keyword of "off-site construction" in Scopus returned 2532 papers. After limiting the publication period to 2010–2020, to the English language, and to conference and journal papers, 885 papers were retrieved related to OSC. The number of published papers appearing yearly on OSC is represented in yellow bars in Figure 4. The next step was to identify the papers related to digital technology utilization among the OSC papers. Fifteen digital technologies identified from Step 1 were applied as keywords to narrow down the search results. The literature search was conducted by inputting keywords into Scopus as follows:

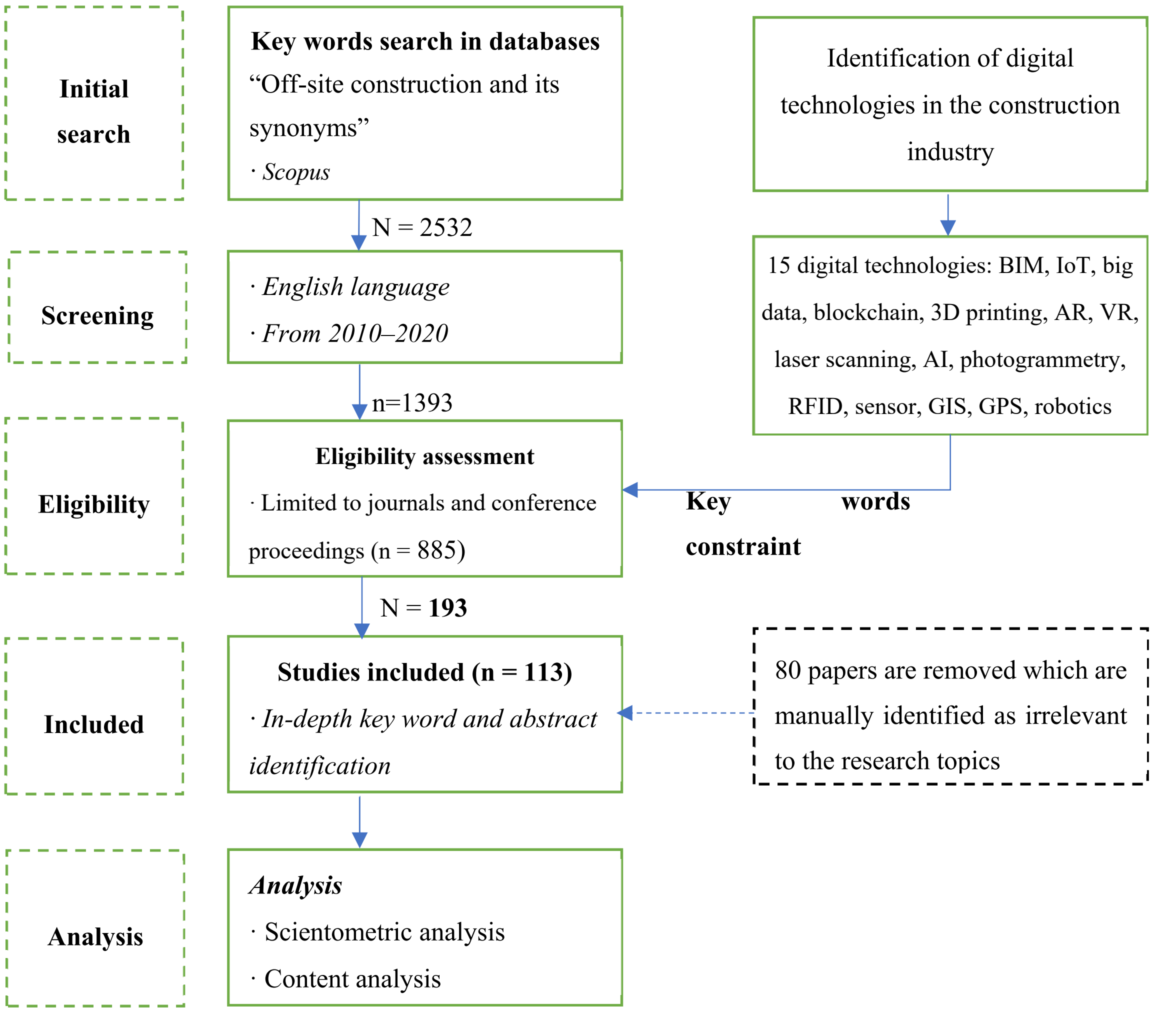

Figure 3. Methodology of conducting the systematic literature review.

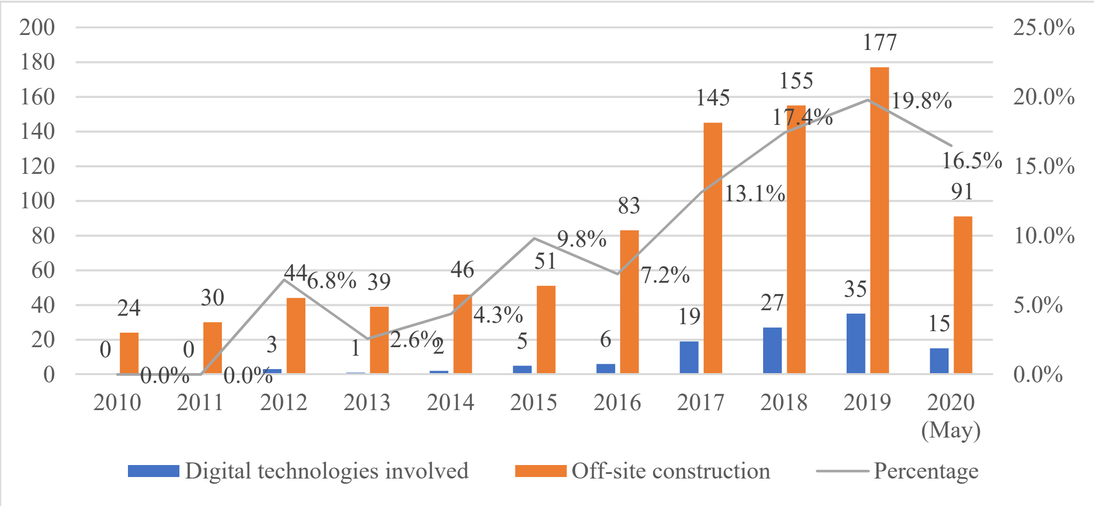

Figure 4. Number of yearly publications of digital technologies involved and total papers in OSC from 2010–2020.

TITLE-ABS-KEY ("precast construction" OR "off-site construction" OR "prefabricated construction" OR "Prefabricated prefinished volumetric construction" OR "on-site assembly" OR "modular building" OR "prefabricated building" OR "Offsite manufacturing" OR "Offsite manufacture" OR "Off-site manufacturing" OR "Off-site manufacture" OR "Off site manufacturing" OR "Off site manufacture") AND TITLE-ABS-KEY ("BIM" OR "building information modelling" OR "IoT" OR "internet of thing" OR "Virtual reality" OR "Augmented reality" OR "AR" OR "VR" OR "Artificial intelligence" OR "deep learning" OR "machine learning" OR "photogrammetry" OR "photometric point cloud" OR "computer vision-based" OR "UAV" OR "photo" OR "image" OR "video" OR "camera" OR "laser scanning" OR "3D sensing" OR "laser scanner" OR "laser scans" OR "RFID" OR "sensor" OR "Global Position System" OR "GPS" OR "Big data" OR "3D printing" OR "addictive manufacturing" OR "3D printer" OR "blockchain" OR "block chain" OR "block-chain" OR "GIS" OR "Geographic Information System" OR "robotics" OR "robotic" OR "robot arm").

Initially, 193 papers were returned in the database. After manual processing, 113 papers were selected as valid papers that are relevant to digital technology utilization in OSC. The annual distribution of the 113 papers is shown as blue bars in Figure 4, in comparison with the annual published papers on OSC. It can be seen that the total number of published papers on digital technology utilization in OSC, accounts for only 12.8% of total papers on OSC from 2010–2020. This suggests that the area is under-explored and the digital technology utilization level is low. In addition, published papers on digital technology utilization in OSC mainly start from 2016, although they are increasing steadily year by year to 2020.

3. Results of Scientometric Analysis

The scientometric analysis is conducted by VOSViewer, which can visualize the influence of key journals, publications, and countries, and analyze the co-occurrence of research keywords, which were commonly adopted key contents in the literature-review-based studies [9,51,54,55]. This section analyzes the co-occurrence of keywords, and the countries active in the targeted research. Moreover, it described a basic background of the targeted research domain and could facilitate further content analysis and qualitative discussions with the mapping results.

3.1. Co-Occurrence of Keywords

The mapping of co-occurrence of author keywords indicates the frequency of occurrence of study topics in one paper and the inter-relatedness among topics [9]. By visualizing the relationships, each keyword can be grouped in a defined category and several clusters that provide information about the main research topic of this literature review. Several main criteria guided the inclusion and exclusion of keywords: (1) The threshold value at a minimum of two co-occurrences; (2) the general keywords such as "construction", "prefabrication", "buildings", "research review", and "literature review" were removed; (3) keywords with the same meaning but using various abbreviations were combined, for example, "BIM", "Building Information Model" and "Building Information Modelling"; and "IoT" and "Internet of Things"; and (4) country names such as "Hong Kong" and "Singapore" were removed as they were analyzed separately. Finally, a total of 26 main keywords were shortlisted and visualized in Figure 5.

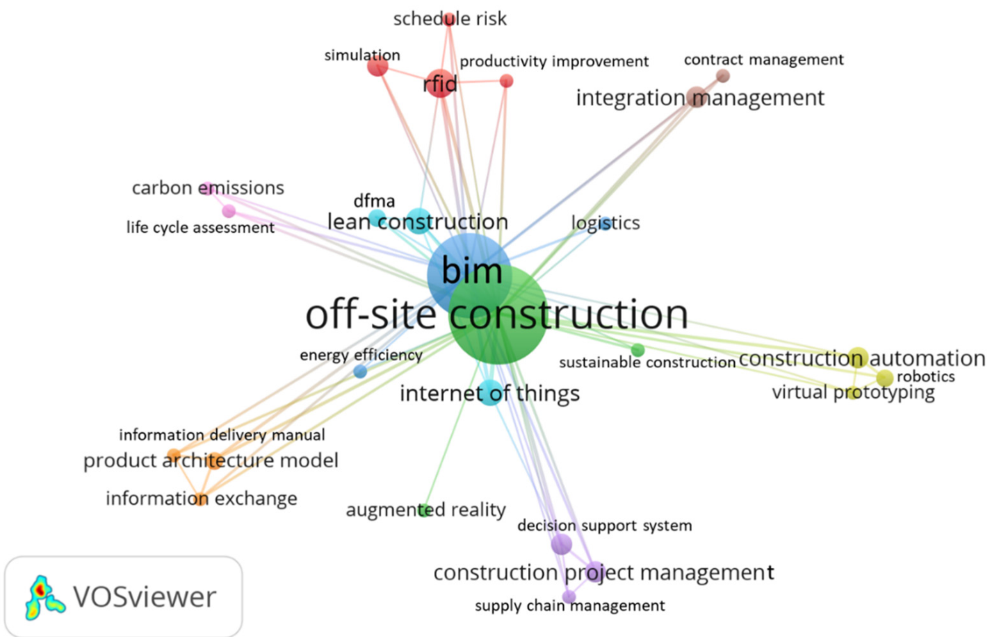

Figure 5. Mapping results of the co-occurrence of author keywords.

As can be seen from Figure 5, BIM is the most frequently used technology in OSC. It is the second biggest circle and is in the center position along with OSC. The items with the same colour represent the same cluster. There are nine clusters reflecting the main research topics of the 113 papers, six of which are clear from the interrelationship analysis:

1. Design for manufacturing and assembly (DfMA) is significant in prefabricated project design. Lean construction aims to improve construction processes by reducing constraints or waste and accelerating construction cycles in OSC. Lean construction is closely linked to DfMA and digital technologies, such as BIM and RFID [56–59], as seen in the light blue circles in Figure 6a;
2. Information delivery and exchange, and the product architect model are to address OSC information sharing issues [52,60–62], as seen in the orange circles in Figure 6b;
3. The estimation of carbon emissions, from additional production and transportation processes in the life-cycle assessment of OSC, is different from traditional construction [63–65]. This cluster is shown in the light purple circles in Figure 6c;
4. Supply chain management is closely linked to the construction project management practice and the decision-making system [60,66,67], as seen in the dark purple circles in Figure 6d;
5. Construction schedule risks are usually dealt with by using simulation and productivity improvement [68–70], as seen in the red circles in Figure 6e;
6. Integration management combines different stages or processes together, such as contract management [46,71], as seen in the brown circles in Figure 6f.

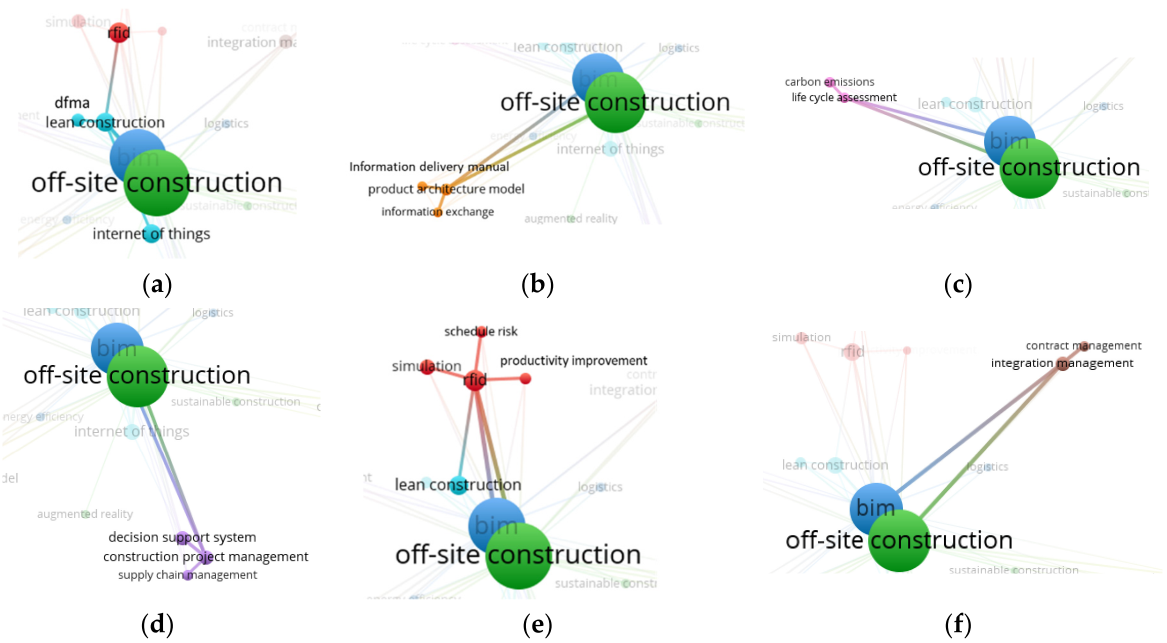

Figure 6. Research topics from clusters: (**a**) Design for manufacturing and assembly (DfMA), (**b**) information delivery and exchange, (**c**) carbon emissions, (**d**) supply chain management, (**e**) schedule risks, (**f**) integration management.

The remaining three clusters are construction automation and robotics, logistics, and sustainable construction. Construction automation is closely related to robotic technology and virtual prototyping [72,73]. Logistics is grouped with BIM and energy efficiency in a dark blue colour [60,74], while sustainable construction is grouped with off-site construction, which indicates that OSC is generally taken as a sustainable approach to building [75–78]. Other keywords identified from this analysis indicate the benefit of OSC, e.g., productivity improvement and energy efficiency.

In summary, the scientometric analysis provided nine research topics from the 113 papers. How digital technologies are linked in these topics need further discussions. Therefore, a more in-depth content analysis is carried out in Section 4.

3.2. Analysis of Countries Involved in Research

This category provides a list of authors and their countries of origin. The minimum number of documents for a country is set to five, and from a total of 25 countries identified from all the literature sources, nine countries meet this requirement, as shown in Figure 7. Table 1 shows the number of citations of papers published by these countries and the link strength with other countries.

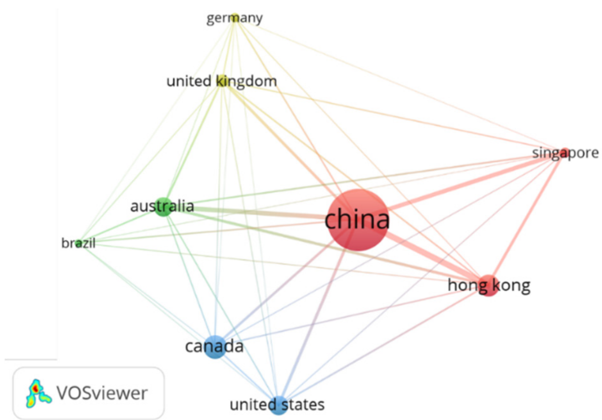

Figure 7. Mapping results of the countries of origin of the published documents.

Table 1. Analysis of the countries of origin of the published documents.

Country	Documents	Citations	Average Citation	Total Link Strength [1]
Mainland China	47	623	13.3	3766
Canada	18	93	5.2	494
Hong Kong (China)	17	487	28.6	2250
Australia	15	81	5.4	1494
United States	15	99	6.6	616
United Kingdom	10	60	6	698
Singapore	8	101	12.6	1211
Germany	7	18	2.6	203
Brazil	6	34	5.7	240

[1] Total link strength means the interrelationship between the given document and other documents.

Mainland China is the most active country in carrying out research on adopting digital technology in OSC, and China is also actively working with other countries and has the highest link strength [27,79–82]. Hong Kong ranked 3rd in the total number of publications, one paper less than Canada, although the citation and link strength with other countries are much higher than Canada. This can be explained by Hong Kong's close link to mainland China. Moreover, Hong Kong's research attracts the highest number of citations in this area, which demonstrates its high quality and the high impact of research in technology applications in OSC.

As for Australia, the total number of published papers is ranked 4th, although the average citation number is 5.4, which is significantly lower than Mainland China, Hong Kong, and Singapore with 13.3, 28.6, and 12.6, respectively, showing its low impact in this field. Canada is in a similar situation with 18 documents ranking 2nd, while the average citation number is 5.2. The link strength between Australia and other countries is still strong with 1494 and ranking 3rd, however. The United States and United Kingdom have smaller total link strengths with 616 and 698, while the average citations are both slightly higher than Australia with 6.6 and 6. Combining the document number, citations, and link strength, it can be concluded that China, Hong Kong, Canada, Australia, the United States, the UK, and Singapore are the main countries carrying out research in adopting digital technologies in OSC.

4. Content Analysis

The scientometric mapping provides nine research topics reflecting the identified literature. However, it cannot demonstrate how the fifteen digital technologies are utilized in each of these topic areas. Following the bibliometric analysis and scientometric mapping, a content analysis was conducted to summarize the current practice of digital technology utilization in OSC, to gain some insight on the purpose of utilizing technologies, the outcomes achieved, and issues of concern.

4.1. Overview and Relationship

As shown in Figure 5, BIM is the most widely analyzed digital technology and it is linked to many other technologies adopted in the OSC. Of the 113 papers, 88 are related to BIM, eight of them being literature review papers on BIM utilization, and the remaining 80 BIM-related papers discussing more specific issues in OSC. To examine how closely BIM is linked to other digital technology adoptions, a careful examination of the 80 non-review papers was carried out. The eight review papers are excluded as they may or may not mention other digital technologies, but as their nature is review, they do not represent new cases of using BIM with other digital technologies. Out of the 80 papers on BIM, 56 papers (70%) focus on BIM alone, meaning that BIM is a digital technology that can be used independently. The remaining 24 papers adopted BIM in conjunction with one or more other digital technologies. The overlap with each of the other technologies is given in Table 2. Note that in Table 2, the percentages do not add up to 100% as the other technologies also overlap with each other. How each digital technology is linked to other technologies is illustrated in Figure 8. Table 2 and

Figure 8 show the current situation of how these digital technologies are linked to each other in OSC. The detailed technology adoption related to the nine topics will be presented in the following sections.

Table 2. Co-occurrence of building information modelling (BIM) with other digital technologies in BIM studies (total number of papers = 80).

Technology		Number of Papers	Proportion
None (BIM only)		56	70%
Co-occurring with other technologies (Total 24 papers, 30%)	RFID	20	25.0%
	GPS	14	17.5%
	IoT	10	12.5%
	Sensor	8	10.0%
	Laser scanning	5	6.3%
	VR	4	5.0%
	Photogrammetry	4	3.8%
	AI	3	3.8%
	Big data	2	2.5%
	AR	1	1.3%
	Blockchain	1	1.3%
	GIS	0	0.0%
	3D printing	0	0.0%
	Robotic	0	0.0%

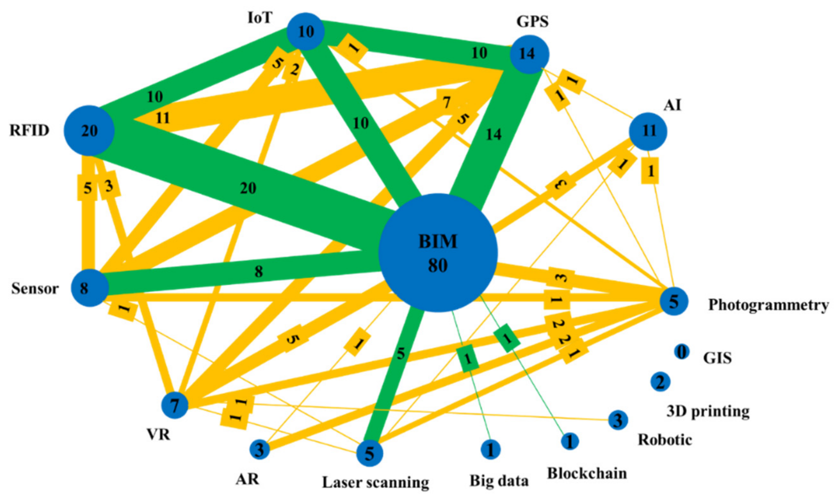

Figure 8. Mapping results of relationships among digital technologies.

Figure 8 shows the dependent relationships between all fifteen technologies. The number in the circle is the total number of papers published on each technology. The number on the thickened bar between any two technologies is the number of the papers adopting both technologies, and the thickness of the bar is proportional to how much the two technologies overlap with each other. In particular, as the green bars indicate, all papers on IoT, GPS, laser scanning, big data, and blockchain, adopted BIM technology at the same time, indicating that they are heavily dependent on BIM. BIM acts as the central "intersection" linking to other technologies. Moreover, note that all 10 papers on IoT are linked to RFID and GPS technologies, as well as BIM. There are no studies on GIS utilization in OSC and 3D printing. Furthermore, robotics, big data, and blockchain are much less explored in OSC currently. In the following section, the use of each of these technologies in OSC is analyzed and discussed.

4.2. Building Information Modelling (BIM)

Eighty eight papers related to BIM adoption in OSC were retrieved from the database including eight review papers, and 80 non-review papers. The major findings of the eight review papers are listed in Table 3, and the major findings for the 80 non-review papers are summarized in Table 4.

The eight review papers summarize different aspects of BIM application in OSC. For example, the authors of [46] carried out a comprehensive review in identifying future directions and the authors of [83] conducted both qualitative and quantitative evaluation of the benefits of BIM for OSC. Three papers reviewed BIM applications in different phases of the project life-cycle [71,84,85]. The balance explored BIM utilization in OSC from structural engineering [86], end-of-life phase [55], and organizational management perspectives [87].

Table 3. Summary of the eight review papers of BIM in OSC.

Review Focus	Main Findings	Limitations	Literature
Comprehensive review of BIM in the off-site manufacturing stage	Emphasis on technology potential, lack of knowledge about clear benefits of BIM and off-site manufacturing is a huge barrier towards OSC's uptake.	It does not discuss how BIM could be used appropriately to fully achieve the benefits.	
Review focus on identifying future directions of BIM for OSC	Through quantitative analysis and in-depth discussion of BIM for OSC, research gaps are identified and future directions are proposed: BIM-based generative design for prefabrication, cloud BIM-based data exchange for OSC, robotics and 3D printing for OSC, BIM-enabled big data analytics toward the best OSC practice.	The directions are more focused on fragment phases or activities. There is a lack of systematic assessment model of BIM in OSC.	[46]
Trending topics and themes in off-site construction research	Used topic-modelling techniques to identify the distribution of topic and themes. Machine learning for language toolkits was used to get topic posterior word distribution and word composition. Identified 50 main topics in OSC, and BIM can be used for organizational management.	Too general or academic in nature with limited practical significance.	[87]
BIM implementation and benefits in different stages of OSC	Examined the potential applications and benefits of BIM in various stages of the entire project lifecycle. Pointed out that most existing research is fragmented with a focus on a specific phase and not on workflow integration.	These reviews are not carried out systematically. They provide a summary or a mapping framework. The conclusions lack quantitative analysis or validation through case analysis.	[71,84,85]
BIM in structural engineering in OSC	Bibliometric analysis of the literature. Current situation: Isolated, disjointed, and fragmented research. Future research should be on modelling of structural components, automation of assembly sequence, planning and optimization of OSC, and dynamic structural health monitoring.	Lacks discussion on practical utilization of BIM, just pointed out that BIM could be a beneficial technology in OSC from a structural engineering viewpoint.	[86]
End-of-life: Minimize construction and demolition	Pointed out the importance of standardized prefabricated modules for rapid on-site assembly. Reusability, circular economy business model, standardization of material types and sizes through prefabrication. MEP prefabrication, RFID-enabled BIM, and traceability regarding features that can enhance end-of-life management.	Not a review focusing on prefabrication construction. Prefabrication/off-site construction is discussed in one section only, and the benefit of reusability of components is also discussed.	[55]

In addition, some of the review papers including [46,55,84,85] show the practical application and benefits of combining other technologies such as RFID with BIM. For example, Luo and Chen [84] showed a BIM-RFID method to store and visualize information. In a different practice, Senthilvel et al. [71] showed the utilization of VR with BIM for identifying construction sequence planning. Moreover, the literature shows that the utilization of laser scanning along with BIM is useful in site inspections for quality control purposes [46,71,86]. In recent practices, the application of AI for generative design along with BIM is discussed by [46], as well as IoT and photogrammetry [46]. The shift from desktop-based BIM to web-based BIM also provided more flexibility and opportunity for BIM usage in OSC supply chain management [88]. In summary, three research gaps can be summarized from these reviews:

1. There is a lack of knowledge on how BIM could be used appropriately to fully achieve its benefit in OSC and a relevant assessment model for measuring those benefits is missing. For example,

how BIM usage in conventional construction projects can benefit a specific area, such as cost estimating, has been discussed in the literature (e.g., [89]), but there has been no such evaluation for OSC;

2. Current discussions on BIM application in OSC are for fragmented phases. How to integrate BIM throughout the OSC project life cycle needs further study;
3. How BIM can be best utilised with other technologies in OSC and especially implemented in real construction practice, is still unclear.

Table 4. Research topics, purpose of BIM adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing BIM	Outcome Achieved	Issues Identified	Key Relevant Literature	Total Number
DfMA	To check and review current plans and find optimal solutions by simulation.	Bathroom pods, wall panels, beams, column, roof, MEP system design and assembly sequence and lift planning optimization, AI technology integrated.	Limited to separate building elements. Less automation of elements' development in BIM, manual intervention.	[56,59,75,90,91]	14
Information delivery and exchange	To visualize information of prefabrication with stakeholders.	Integrate RFID, GPS, sensors, image, scan data with designed BIM model for near-real-time construction monitoring and communication.	Lack of standardization, information loss. Poor understanding among different stakeholders.	[10,92–95]	20
Carbon emissions	To carry out carbon emission analysis.	Emissions reduction, labour and cost saving, accuracy of decision-making improved.	Lack of data accuracy test.	[64,65]	2
Supply chain management	To streamline and visualize components production, transportation, and on-site assembly activities.	Visualize real construction progress. Automation and information sharing level improved. Cost and time saving.	Lack of procurement process, safety management, and fidelity with actual practice. Poor connections among RFID, sensors. Different data format brings poor communication.	[7,74,96–98]	9
Schedule risks	To detect quality of components by comparison with near-real-time collected data.	Cost and labour saving, time saving, e.g., 20%. Schedule risks reduction, rework reduction onsite, information sharing efficiency improved.	Complexity of data processing, manual intervention, poor automation in data alignment with others, e.g., RFID data.	[99–103]	15
Logistics	To make collaboration in planning and control meetings, reviewing logistics plans.	Productivity improves, e.g., 38% labour reduction, waiting time reduced, e.g., 20%, work-in-progress inventory reduced, on-time delivery rate improved, e.g., 7.3%.	Lack of intelligent decision-making models, lack of components library and optimization algorithms, limited case validation, manual intervention.	[68,104–107]	6
Sustainable construction	To make energy reduction analysis, integrated with leanness concepts for simulation analysis.	Waste reduction and reusing components strategies, life cycle management of elements.	Limited BIM usage in end-of-life of precast elements and recycle strategies, manual intervention, skilled labour needed.	[75–77]	13
Integration management	To conduct empirical analysis on effects of BIM in OSC.	BIM is able to improve the performance of OSC through its integration management and cooperation.	Lacks an estimate of the actual improved performance from BIM implementation.	[108]	1

The 80 non-review papers related to BIM discussed a wide range of issues in OSC and the research topics (as identified and categorized in Section 3.1) associated with them are summarized in Table 4.

Based on the identified issues, the future directions for BIM utilization in OSC are suggested as follows:

1. BIM-based automated design and optimized planning to coordinate prefabricated elements rather than separate parts design. AI is a promising technology to support an automated assembly process;

2. Developing BIM standards for data exchange and delivery among different stakeholders considering the characteristics of OSC projects, as well as BIM integration and communication with other technologies data, such as sensors, RFID, point cloud to reduce information loss, and improve data processing efficiency;
3. More functions can be added in BIM to reflect actual practices of supply chain management and on-site management of OSC, such as procurement processes, safety management, quality management, and environment issues;
4. AI could be integrated into BIM to facilitate complex data processing and decision-making in project schedule risk identification and logistics optimization;
5. Recycling strategies for end-of-life prefabrication materials should be further developed for sustainable development;
6. BIM utilization throughout the entire life cycle in OSC needs to be streamlined;
7. More case studies need to be conducted to evaluate the actual improvement resulting from BIM implementation, and to help develop an assessment model for measuring the benefits of BIM utilization in OSC projects;
8. The integration and arrangement of other technologies (e.g., RFID, sensors) with BIM in OSC need to be developed in a more scientific way to be aligned with OSC processes and leverage the benefit of each technology with less effort.

4.3. Radio Frequency Identification Devices (RFID)

There are two types of RFID systems. One is called a passive system without any power source and the other is called an active system with a battery in tag. Most papers on RFID in OSC discuss the passive RFID system [96,98,109]. A passive RFID system usually includes an antenna, RFID reader, and tag [77,89]. The tags are always attached to tools, machinery, and materials and then the status and numbers of targeted objects can be quickly detected and recorded near-real-time in digital data [81,89,90]. There are 20 RFID papers describing the application in OSC, and all 20 use BIM simultaneously. The main topics, the purpose of adopting RFID, and the outcomes achieved in these papers are listed in Table 5.

Based on the identified issues, the future directions for RFID utilization in OSC are suggested as follows:

1. Better performing devices need to be adopted in OSC with better signal range and strength, reduction of damage, faster reaction speed, such as active RFID, and improved working capacity in the concrete environment of prefabricated components;
2. The design of a RFID arrangement plan of tags number, installation position, RFID selection should be detailed and analyzed before implementation;
3. The RFID data reliability needs to be further tested and enhanced for accuracy to meet industry requirements for OSC projects—for supply chain management, logistics, and schedule risks identification;
4. A more efficient way should be developed to simplify data processing from raw RFID data and reach global standardization of RFID data representation;
5. Data security issues need to be addressed in logistics planning and asset management.

Table 5. Research topics, purpose of radio frequency identification devices (RFID) adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing RFID	Outcome Achieved	Issues Identified	Relevant Literature
Supply chain management	To automatically identify near-real-time object information.	Simulation validated the improvement of efficiency, e.g., 62.0% saving of operational costs; streamlined process.	Well-designed BIM model required. Disjointed connections among RFID and BIM.	[69,74,76,101,110]
	To track status of material.	Reduction of information loss, efficiency improved, time and labour cost savings.	Limited range of signals, and inaccurate data from damaged 1.5% RFID tags, manual intervention.	[96–98]
Carbon emissions	To identify each component with material usage.	Rough emission calculation and emission risks reduction.	Lack of data reliability test, e.g., accuracy and reaction speed.	[64]
Schedule risks	To track labour, materials, and equipment use.	50%-time reduction of façade installation. Overall 20% reduction of scheduled time.	Complexity of raw RFID data processes. Lack of detailed tags arrangement plan.	[102,103,106,111]
Logistics	To detect the status of elements for asset management.	Low cost and timely transportation data collection.	Complexity of raw RFID data process, data security issues.	[68,105]
Information delivery and exchange	To collect the near-real-time status of components.	Near-real-time progress and cost information integrated with BIM.	Lack of global standards for RFID data exchange.	[7,67,112]

4.4. Global Positioning System (GPS)

There are 14 papers describing the application of GPS in OSC, which suggest that OSC could be effectively improved by applying the system [49]. GPS is a digital technology that could provide location information in near-real-time and create smart construction objects, including components, materials, vehicles, and machinery [77]. The implementation of GPS technology is straight forward, since it can be integrated into a smart phone for the detection of components [78,85]. The main topics, purpose of adopting GPS, and outcomes achieved in these papers are listed in Table 6.

Table 6. Research topics, purpose of global positioning system (GPS) adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing GPS	Outcome Achieved	Issues Identified	Relevant Literature
Supply chain management	To detect coordinates of precast components for load and unloading information.	Efficiency improved, cost and time saving for information collection.	Temporary data storage and not real-time, e.g., 1–2 min waiting time for data collection.	[69,96–98,103]
Carbon emissions	To measure transportation route and distance.	Material consumption and emissions can be estimated rapidly.	Lack of data reliability, e.g., accuracy and reaction speed.	[64,65]
Schedule risks	To collect coordinates information of building elements to compare with BIM.	Timely decision-making, errors reduction, time saving.	Lak of data reliability test, e.g., accuracy and response speed.	[7,103,112,113]
Logistics	To capture near-real-time information about components.	Time saving, information sharing improved.	Time consuming data extraction and process, manual intervention.	[68,105,114]

Based on the identified issues, the future research directions for GPS utilization in OSC are suggested as follows:

1. GPS data accuracy, data storage capacity analysis, and near-real-time data reaction speed should be further validated in actual prefabricated local OSC projects;
2. A more automated way of GPS data collection and a more intelligent way of data extraction should be designed in logistics and supply chain management taking into consideration the OSC features.

4.5. Internet of Thing (IoT)

IoT is a system with multiple technologies, which may include sensors, networks, the cloud, analytics, and user interfaces to transmit and record information among different processes and stakeholders in near-real-time [96,97,115]. There are 10 papers discussing IoT applications in OSC, all of them involving BIM as the central technology to analyze collected data with the designed model. These papers are listed in Table 7.

Table 7. Research topics, purpose of the Internet of Things (IoT) adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing IoT	Outcome Achieved	Issues Identified	Relevant Literature
Supply chain management	To achieve near-real-time visibility and traceability in OSC.	Time and cost saving, information sharing, and automation level improved.	Delays caused by unstable network signals, complexity in data processing.	[96–98]
Logistics	To realize automatic data collection and item-level management.	Information and automation level of cost and progress information improved, efficiency increased.	Time and money consumed to develop IoT, and security and privacy issues.	[68,105]
Information delivery and exchange	To monitor progress and cost in on-site assembly.	Efficiency improvement by timely information sharing.	Incomplete function modules for daily operations, e.g., quality, safety, without industrial standards among technologies.	[7,60]
Carbon emissions	To collect and visualize emissions.	Emissions reduction, labour and cost saving, accuracy of decision-making improved.	Lack of data reliability test, e.g., accuracy and reaction speed.	[64]

The IoT applications in construction have heavily relied on various integrated technologies such as RFID, sensors, and BIM. This part mainly concentrates on the framework design of IoT and the existing barriers to implementation. The future directions for IoT utilization in OSC are suggested as follows:

1. Network signals need to be enhanced with higher stability for information exchange and delivery; data accuracy and delivery speed should be tested for actual OSC daily operation requirements;
2. Security and privacy issues in project data exchange and storage for logistics management need to be addressed;
3. The IoT system should be enhanced through a quality check of prefabricated components in manufacture, transportation and assembly processes, construction safety management, and environmental protection issues;
4. Industrial standards, which are more applicable to OSC projects, should be developed among BIM, GPS, RFID, and other technologies;
5. More practical tests need to be conducted for implementation in real-life, off-site projects rather than simulation by virtual models.

4.6. Sensors

Sensors are devices that can generate electronic signals from a physical condition and collect information such as temperature, pressure, location, and carbon emissions, as seen in Table 8.

Table 8. Type of sensors.

Sensor Type	Function	Reference
GPS sensors	Location identification of components; detect and transmit the running time of construction machineries.	[64,65,116]
Strain sensors	Measure the near-real-time strain on structural elements.	[117]
Acceleration sensors	Monitor the operational status of tower cranes.	[64,65]
Barometric sensors	Monitor the running state of construction elevators.	[64,65]
Wind-sensor, rain-sensor	Monitor wind speed and rain load.	[112]
Fibre optic sensor	Automate processes by activating the RFID reader and GPS receiver.	[69]
Laser sensor	Determine manufacturing time of equipment.	[64]

Ten papers are identified in this study which are applied in OSC. The main topics, purpose of using sensors, and outcomes achieved in these papers are listed in Table 9.

Table 9. Research topics, purpose of sensors adoption, and outcomes achieved in previous studies.

Topics	Purpose of Utilizing Sensors	Outcome Achieved	Issues Identified	Relevant Literature
Information delivery and exchange	To monitor the structural health of prefabricated components.	Damage identification of buckled or yielded steel in near-real-time, visualized based on BIM system.	Difficulty in full integration between physical sensors and data uploading, and data processing.	[117]
Carbon emissions	Near-real-time monitoring of carbon emissions of material usage and machinery operation.	Timely reduction of irregular emissions and labour cost.	Lack of data reliability, e.g., accuracy and reaction speed.	[64,65]
Supply chain management	To create smart construction objects for virtual environment development.	Location identification of prefabricated components.	Lack of practical analysis, and needs to improve ease of installation and maintenance.	[69,97,98]

Based on the identified issues, the future directions for sensor utilization in OSC are suggested as follows:

1. The application of sensors needs to be extended to other types of projects such as precast concrete components, and more suitable sensors need to be tested for the effective detection of other types of damage that occurs in prefabricated components;
2. More effective methods need to be developed to link the physical sensors with virtual sensors for efficient information delivery and exchange;
3. Installation and maintenance of sensors in prefabricated concrete components and steel needs to be improved, and sensor layout plans need to be detailed and costed before implementation in real cases;
4. To develop cost reduction strategies by identifying critical prefabricated components rather than installing sensors on all prefabricated components.

4.7. Augmented Reality (AR)

AR is a computer-based technology by which virtual data can be added to the user's perception of the real world and provide a highly immersive experience to the user [118]. This technology can be used for inspection, tracking, and modification of on-site construction tasks [119]. Utilizing AR, the quality of tasks can rely less on workers' experience and reduce on-site paper-based procedures.

There are three papers related to AR technology applications in the OSC database. The main topics, outcomes achieved, and issues identified are given in Table 10.

Table 10. Research topics, purpose of augmented reality (AR) adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing AR	Outcome Achieved	Issues Identified	Relevant Literature
Schedule risks	To reduce errors of on-site assembly and repair tasks.	75% reduction of errors on assembly tasks and 90% time saving for developing the same type of prototype.	Software based and lack of model accuracy validation with real world.	[52]
	Inspect prefabrication element with the 3D AR model.	Monitor quality of precast elements and make photographic, scanned 3D model, and stroke-type annotates with the AR-based tool.	AR makers are required, high requirement of equipment and environment conditions, time consuming for algorithm design and manual intervention, complexity of device operation.	[118,120].

Based on the identified issues, the future directions for AR utilization in OSC are suggested as follows:

1. Integrating AI in AR algorithm development to encourage time and cost saving;
2. Utilizing AR to improve efficiency and precision of the assembly process in OSC;
3. Developing innovative methods which are less dependent on equipment and environmental conditions for OSC projects;
4. Integrating laser scanning into AR for creating a near-real-time virtual environment for quality checking of OSC building components.

4.8. Virtual Reality (VR)

Compared with AR, VR technologies are mainly studied in lift planning in relation to off-site projects, as seen in Table 11. Moreover, VR can be integrated with AR as a mix reality (MR) [120]. The main limitation is that 3D objects in VR are identified as phantom models compared with the real-world counterparts, that is, an animation rather than real representation, therefore, critical information such as the level of quality achieved might be lost [72,120–122].

Table 11. Research topics, purpose of virtual reality (VR) adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing VR	Outcome Achieved	Issues Identified	Relevant Literature
Schedule risks and logistics	To guide production process, e.g., crane lifting in a safer and more efficient way.	Enhancement of site safety and productivity with VR-supported tool.	Based on virtual environment simulation which may not accurately replicate real situations, and operators are not able to see themselves on the screen.	[72,121,122]
	To present near-real-time construction progress.	Integrated as a functional module in a platform.	Mainly at conceptual and virtual model presentation stage. Lack of practical outcomes and tests in real cases.	[7,96,103]

Based on the identified issues, possible future directions for AR utilization in OSC are suggested as follows:

1. Validate VR utilization in a real OSC environment for monitoring lift activities and near-real-time progress rather than relying on simulations;
2. To enhance the fidelity of the VR environment and make the operators feel more immersed in linking VR with the real construction environment;
3. Developing assessment models of VR performance to measure efficiency improvement and reduce errors.

4.9. Photogrammetry

There are five papers related to photogrammetry technology and its application in OSC. The two main topics and research outcomes are seen in Table 12. This technology is mainly used to achieve on-site quality control, since it can capture near-real-time image data from the construction site [123]. For example, the information about texture, size, configuration, location, arrangement of the components, and even workers' facial expression of fatigue, for example, could be captured by images or videos and then visualized in a point cloud processing platform [112,123,124]. The collected data are mainly used to compare with BIM models or VR/AR technologies [112].

Table 12. Research topics, purpose of photogrammetry adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing Photogrammetry	Outcome Achieved	Issues Identified	Relevant Literature
Schedule risks	Quality detection by identifying geometry deviation.	Quality detection for light-gauge steel frame, intersection, and stud detection of rectangular forms.	Inaccurate for irregular components, e.g., door or window, and limitations of camera location, and lack of accurate analysis.	[123]
	To detect crane operators' fatigue.	93.6% overall accuracy could be achieved in fatigue detection.	Insufficient features related to fatigue identified from images.	[124]
Information delivery and exchange	To capture near-real-time information of objects for development of a virtual environment.	Re-optimizing crane lifting paths simulated in a BIM environment.	Lack of analysis and photographic data of real cases and how the image data are exchanged with the BIM model.	[112]
	To capture the construction site and integrate with a BIM model for supervision.	Combine near-real-time on-site data with BIM model and detect progress differences by superimposing building elements in an A/VR environment.	Pre-set markers required for information extraction from images or videos. Alignment with BIM model is not automated.	[118,120]

Based on the identified issues, possible future directions for photogrammetry utilization in OSC are suggested as follows:

1. Extending photogrammetry usage in quality detection to precast concrete projects rather than only steel or wood projects, and recognition of the irregularly shaped precast components;
2. Optimization of photogrammetric devices to improve image quality for higher accuracy and reduce the complexity of data processing based on the real OSC environment;
3. Developing methods for automated data alignment and data exchange with BIM models to facilitate near-real-time lifting task optimization and construction progress monitoring;
4. Further testing and enhancement of image data reliability for improving accuracy and processing speed to meet industry requirements for OSC projects;
5. Improving the accuracy of on-site workers' operations (e.g., for crane operators) and their status for safety purposes.

4.10. Laser Scanning

There are five papers related to laser scanning technology's application in OSC. The main topic and outcomes are listed in Table 13. Laser scanning could capture point cloud data with geometric, colour, and coordinate information for both objects and the environment generally [125,126]. There are different types of mobile and terrestrial scanners with different levels of accuracy and quality [126], and the literature discusses a wide range of practices of using point cloud data in information systems or models in the construction field [127].

Table 13. Research topics, purpose of laser scanning adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing Laser Scanning	Outcome Achieved	Issues Identified	Relevant Literature
Schedule risks	Quality detection by identifying geometric deviation.	Improved efficiency in detecting modular elements in the shape of a cylinder and rectangle, in comparison with the as-designed BIM model.	Incomplete collected data with occlusion or noise. Complex data process in need of skilled manual processing. Limited elements identification.	[125,128,129]
Information delivery and exchange	Height measurement.	To determine the height of a single steel frame in the loading area, and data exchange with the BIM model.	Laser scanner system may not be suitable for large-size manufactured parts due to high cost and complex implementation process.	[123,125]
	To capture the specific construction scene for a virtual environment creation.	Safety improvement by identifying potential obstacles during the construction lifting process.	The objects from a point cloud are created manually and approximately.	[121]

The laser scanning technology is widely discussed in the traditional construction area connected with progress control [130,131], object recognition [132], change detection [133], and creating part-built [126] and as-built models [134,135]. However, the application to OSC is limited. Based on the identified issues, the future directions for laser scanning utilization in OSC are suggested as follows:

1. Processing capability improvement to enhance data accuracy and efficiency for quality detection of both regular and irregular precast components;
2. Utilizing AI technology to increase the level of automation to reduce dependency on manual intervention in data creation and data processing;
3. Developing methods for more accurate data collection using laser scanning and data noise reduction;
4. Increasing the adoption of laser scanning technology in the OSC practice in a wider range of construction quality control, progress monitoring, and safety management.

4.11. Artificial Intelligence (AI)

As mentioned previously with many other digital technologies, AI can be used to improve the efficiency and accuracy of other technologies. There are 11 papers related to AI technology application in OSC. The research topics, outcomes achieved, and issues identified are presented in Table 14.

Table 14. Research topics, purpose of artificial intelligence (AI) adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing AI	Outcome Achieved	Issues Identified	Relevant Literature
DfMA	To assist optimizing the design of prefabricated components.	Reduced effort and cost; high process speed in components' segmentation with optimization algorithms.	Time consuming on preparation of topology analysis; limited elements configuration design.	[12,136–138]
Logistics	To estimate transportation cost.	Improved estimation method; 14% calculation error reduction.	Complex calculation with a large amount of data.	[114]
Schedule risks	To optimize or predict the construction tasks.	Monitoring the on-site construction progress by automated comparison between actual and planned model, variability and tolerance control on product quality, and identifying on-site risks e.g., crane operator fatigue.	lack of real practice validation. In need of large amounts of data for training, and time consuming.	[7,124,128,137]
Supply chain management	To optimize supply chain management and assist selecting factory locations.	Test on decision making of cost reduction and effectiveness of alternative methods.	Lack of consideration of real projects and the context conditions.	[139,140]

Based on the identified issues, the future directions for AI utilization in OSC are suggested as follows:

1. AI-based design for topology analysis of prefabricated elements—configuration, segmentation, and optimization;
2. Complex data analysis in logistics data processing;
3. Distance determination of factory location and construction site before OSC and optimization of supply chain management to reduce costs;
4. Prediction of various potential project risks based on historical and real-time data.

4.12. 3D Printing

There are two papers related to the 3D printing technology and its application in OSC. The research topics, outcomes, and issues identified are presented in Table 15.

Table 15. Research topics, purpose of three-dimensional (3D) printing adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing 3D Printing	Outcome Achieved	Issues Identified	Relevant Literature
Sustainable construction	To make formwork with 3D printing and compare the results with traditional methods.	3D printing could improve accuracy and save time and costs for curved formwork compared with the conventional method.	Limited to regular shapes and materials, and needs to be extended to complex precast components.	[141]
	To clarify the confused attributes between construction, 3D printing, and traditional construction.	Put forward the method of cost calculation of 3D printing in OSC, and it contributed in solving the problems of cost calculation among different construction technologies.	Lack of real case validation for the proposed approach.	[142]

Based on the identified issues, possible future directions for 3D printing utilization in OSC are suggested as follows:

1. Enhance 3D printing to be able to handle complex and irregular prefabricated components effectively;
2. Improve cost, accuracy, and mechanical performance of 3D printing for precast components;
3. Implement 3D printing to real case OSC projects to validate the approach and demonstrate its efficiency.

4.13. Robotics

There are three papers related to robotic technology application in OSC. The research topics, outcomes, and issues identified are presented in Table 16.

Table 16. Research topics, purpose of robotics adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing Robotics	Outcome Achieved	Issues Identified	Relevant Literature
Sustainable construction	To design a robotic machine or automation strategies for manufacturing.	Rebar cages or precast timber—automated production simulated, e.g., VR model simulating the proposed mechanism with optimum performance.	Design at a virtual level. Lack of physical prototypes validation. Lack of cost analysis for adoption.	[72,73]
	To explore the determinants of robotics adoption in precast concrete production.	Environmental and organizational contexts are more critical than technological advancements for adoption.	Only four cases are available for analysis.	[143]

Based on the identified issues, the future directions for robotic utilization in OSC are suggested as follows:

1. Conducting cost analysis studies for robotic utilization in the manufacturing process;

2. Testing the onsite assembly process of robotic utilization using physical prototypes before implementation to provide adequate information and evidence for decision making.

4.14. Big Data

There is only one paper related to big data technology application in OSC. The research topics, outcomes, and issues identified are presented in Table 17.

Table 17. Research topics, purpose of big data adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing Big Data	Outcome Achieved	Issues Identified	Relevant Literature
Supply chain management	To analyze big data utilization in OSC.	An introductory paper on big data application in design, production, and on-site assembly stages.	Lack of empirical validation and case study. Mainly at a conceptual level.	[144]

Based on the identified issues, the future direction for big data utilization in OSC is that more empirical validation and case studies can be conducted. Big data has great potential to be utilized in supply chain management to improve its efficiency, but can also be expanded to other areas of OSC such as component design analysis, construction cost, and time analysis.

4.15. Blockchain

There is only one paper related to blockchain technology and its application in OSC. The research topics, outcomes, and issues identified are shown in Table 18.

Table 18. Research topics, purpose of blockchain adoption, and outcomes achieved in previous studies.

Topic	Purpose of Utilizing Blockchain	Outcome Achieved	Issues Identified	Relevant Literature
Supply chain management	To realize near-real-time traceability and information sharing with all precast components information in smart contracts.	Reduction of supply chain cost, ranging from 38 to 99.8% in different scenarios improved efficiency.	Currently at a simulation level, and lack of validation in real case studies. Processing time consuming with the approval of all stakeholders needed. Data security issues.	[145]

Based on the identified issues, the immediate future directions for blockchain utilization in OSC are smart contract management, addressing the security issues, and achieving a faster approval process.

5. Conclusions

This research was inspired by the recent Industry 4.0 phenomena, which is fueled by technology advancement and innovations for improving efficiency and productivity in all fields. As pointed out by the authors of [146], the growth of the construction industry is a subset of the universal set of gross domestic product value, and OSC is an important area to be developed to drive the revolution in the construction industry. Due to the nature of OSC, the successful implementation of OSC heavily relies on technology utilization. Many scholars have utilized a variety of digital technologies to improve the productivity of OSC, although no research has been found to systematically summarize the current practice of technology adoption in OSC and provide directions for future study. This paper fills the gap and the major contributions are summarized below:

This review identified the 15 most commonly used digital technologies in the construction industry based on publications in the Scopus database during the period from 2010–2020 and then, adopted them as keywords to carry out a detailed literature search for their utilization in OSC during the same period. It was found that China, Hong Kong, Canada, Australia, the United States, the UK, and Singapore are the main countries carrying out research on adopting digital technologies to improve

OSC processes. However, overall, only a small portion (12.8%) of the research publications related to OSC utilizes digital technologies, which indicates that there is still great potential to implement digital technologies to improve the OSC processes.

Based on the VOSviewer visualization of keywords, the research papers related to technology utilization in OSC are grouped under nine research topics. These nine research topics in OSC are used to guide and classify the content analysis of each digital technology's utilization in OSC. Three research topic areas of OSC including schedule risks, information delivery and exchange, and DfMA have received the most attention by scholars in utilizing digital technologies in OSC.

In the content analysis of the retrieved papers, each technology is individually analyzed, and the details about the purpose of utilizing each technology, the outcomes achieved, and issues with each technology are presented in tables for easy reference. Based on the identified issues, the potential future research direction of each technology is discussed.

In summary, among the identified technologies, BIM, IoT, RFID, and VR/AR are the most frequently mentioned among all the reviewed papers. BIM, as a concept, a methodology, or a technology has been applied in the construction industry for decades and is in the center to link other newer technologies emerging in the Industry 4.0 revolution. It remains in its important position to facilitate the implementation of other technologies in the construction industry.

BIM, RFID, and GPS have been developed for relatively longer in the industry, and are technologically mature, and in a state of "ready to use" for OSC projects. The main issue with these technologies are the need for relevant and applicable industry standards in consideration of OSC characteristics to facilitate a more efficient adoption. VR/AR, photogrammetry, laser scanning, and AI are relatively less explored in OSC, but they could be very effective in improving OSC performance and have great potential to be further developed.

The application of all the reviewed digital technologies may contribute to further productivity and efficiency improvement for OSC. However, to effectively utilize these technologies, research and development in some specific areas is still needed and this paper has provided a clear direction. OSC, once it realizes its full potential, will reshape the future construction industry and bring us into a construction 4.0 era.

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References

1. Staib, G.; Dörrhöfer, A.; Rosenthal, M. *Components and Systems: Modular Construction–Design, Structure, New Technologies*; Birkhauser Verlag AG: Basel, Switzerland, 2013.
2. Arashpour, M.; Wakefield, R.; Abbasi, B.; Arashpour, M.; Hosseini, R. Optimal process integration architectures in off-site construction: Theorizing the use of multi-skilled resources. *Archit. Eng. Des. Manag.* **2018**, *14*, 46–59. [CrossRef]
3. Fenner, A.E.; Zoloedova, V.; Kibert, C. *Conference Report 2017: State-of-the-Art of Modular Construction*; University of Florida: Gainesville, FL, USA, 2017. [CrossRef]
4. Ferdous, W.; Bai, Y.; Ngo, T.D.; Manalo, A.; Mendis, P. New advancements, challenges and opportunities of multi-storey modular buildings—A state-of-the-art review. *Eng. Struct.* **2019**, *183*, 883–893. [CrossRef]
5. Kamali, M.; Hewage, K. Life cycle performance of modular buildings: A critical review. *Renew. Sustain. Energ. Rev.* **2016**, *62*, 1171–1183. [CrossRef]
6. Lawson, M.; Ogden, R.; Goodier, C. *Design in Modular Construction*; CRC Press: Boca Raton, FL, USA, 2014.
7. Li, C.Z.; Xue, F.; Li, X.; Hong, J.; Shen, G.Q. An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction. *Autom. Constr.* **2018**, *89*, 146–161. [CrossRef]

8. Gan, X.; Chang, R.; Zuo, J.; Wen, T.; Zillante, G. Barriers to the transition towards off-site construction in China: An Interpretive structural modeling approach. *J. Clean. Prod.* **2018**, *197*, 8–18. [CrossRef]
9. Jin, R.Y.; Gao, S.; Cheshmehzangi, A.; Aboagye-Nimo, E. A holistic review of off-site construction literature published between 2008 and 2018. *J. Clean. Prod.* **2018**, *202*, 1202–1219. [CrossRef]
10. Hwang, B.-G.; Shan, M.; Looi, K.-Y. Key constraints and mitigation strategies for prefabricated prefinished volumetric construction. *J. Clean. Prod.* **2018**, *183*, 183–193. [CrossRef]
11. Gibb, A.G. *Off-Site Fabrication: Prefabrication, Pre-Assembly and Modularisation*; John Wiley & Sons: Hoboken, NJ, USA, 1999.
12. Hwang, B.-G.; Shan, M.; Looi, K.-Y. Knowledge-based decision support system for prefabricated prefinished volumetric construction. *Autom. Constr.* **2018**, *94*, 168–178. [CrossRef]
13. Goh, M.; Goh, Y.M. Lean production theory-based simulation of modular construction processes. *Autom. Constr.* **2019**, *101*, 227–244. [CrossRef]
14. Akbarnezhad, A. Modular vs conventional construction: A multi-criteria framework approach. In Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC), Taipei, Taiwan, 28 June–1 July 2017; pp. 214–220.
15. MBI. *2018 Permanent Modular Construction Report*; Modular Building Institute: Charlottesville, VA, USA, 2018.
16. Mah, D.; Al-Hussein, M. An integrated evaluation framework for sustainable residential construction. *Int. J. Interdiscip. Soc. Sci.* **2008**, *3*, 129–135. [CrossRef]
17. Murtaza, M.B.; Fisher, D.J.; Skibniewski, M.J. Knowledge-based approach to modular construction decision support. *J. Constr. Eng. Manag.* **1993**, *119*, 115–130. [CrossRef]
18. Liu, H.; Singh, G.; Lu, M.; Bouferguene, A.; Al-Hussein, M. BIM-based automated design and planning for boarding of light-frame residential buildings. *Autom. Constr.* **2018**, *89*, 235–249. [CrossRef]
19. Alwisy, A.; Hamdan, S.B.; Barkokebas, B.; Bouferguene, A.; Al-Hussein, M. A BIM-based automation of design and drafting for manufacturing of wood panels for modular residential buildings. *Int. J. Constr. Manag.* **2019**, *19*, 187–205. [CrossRef]
20. Banihashemi, S.; Tabadkani, A.; Hosseini, M.R. Integration of parametric design into modular coordination: A construction waste reduction workflow. *Autom. Constr.* **2018**, *88*, 1–12. [CrossRef]
21. Lin, X.; Lu, Y.; Liu, J.B. Research on Mathematical Model of Cost Budget in the Early Stage of Assembly Construction Project Based on Improved Neural Network Algorithm. *Math. Probl. Eng.* **2020**, *2020*, 3674929. [CrossRef]
22. Xie, L.; Chen, Y.; Xia, B.; Hua, C. Importance-Performance Analysis of Prefabricated Building Sustainability: A Case Study of Guangzhou. *Adv. Civ. Eng.* **2020**, *2020*, 8839118. [CrossRef]
23. Shahpari, M.; Saradj, F.M.; Pishvaee, M.S.; Piri, S. Assessing the productivity of prefabricated and in-situ construction systems using hybrid multi-criteria decision making method. *J. Build. Eng.* **2020**, *27*. [CrossRef]
24. Sabine, H.; Paul, T.; Ethan, C. *Prefabrication: The Changing Face of Engineering and Construction, 2017 FMI/BIMForum Prefabrication Survey*; FMI: Raleigh, NC, USA, 2017.
25. Hong, J.; Shen, G.Q.; Li, Z.; Zhang, B.; Zhang, W. Barriers to promoting prefabricated construction in China: A cost–benefit analysis. *J. Clean. Prod.* **2018**, *172*, 649–660. [CrossRef]
26. Mao, C.; Xie, F.; Hou, L.; Wu, P.; Wang, J.; Wang, X. Cost analysis for sustainable off-site construction based on a multiple-case study in China. *Habitat Int.* **2016**, *57*, 215–222. [CrossRef]
27. Qi, Y.; Chang, S.; Ji, Y.; Qi, K. BIM-based incremental cost analysis method of prefabricated buildings in China. *Sustainability* **2018**, *10*, 4293. [CrossRef]
28. Arashpour, M.; Kamat, V.; Bai, Y.; Wakefield, R.; Abbasi, B. Optimization modeling of multi-skilled resources in prefabrication: Theorizing cost analysis of process integration in off-site construction. *Autom. Constr.* **2018**, *95*, 1–9. [CrossRef]
29. Razkenari, M.; Fenner, A.; Shojaei, A.; Hakim, H.; Kibert, C. Perceptions of offsite construction in the United States: An investigation of current practices. *J. Build. Eng.* **2020**, *29*. [CrossRef]
30. Hong, J.; Shen, G.Q.; Mao, C.; Li, Z.; Li, K. Life-cycle energy analysis of prefabricated building components: An input–output-based hybrid model. *J. Clean. Prod.* **2016**, *112*, 2198–2207. [CrossRef]
31. Kabirifar, K.; Mojtahedi, M.; Wang, C.; Tam, V.W.Y. Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: A review. *J. Clean. Prod.* **2020**, *263*. [CrossRef]

32. Wang, C.C.; Sepasgozar, S.M.E.; Wang, M.; Sun, J.; Ning, X. Green performance evaluation system for energy-efficiency-based planning for construction site layout. *Energies* **2019**, *12*, 4620. [CrossRef]
33. Alazzaz, F.; Whyte, A. Linking employee empowerment with productivity in off-site construction. *Eng. Constr. Archit. Manag.* **2015**, *22*, 21–37. [CrossRef]
34. Gan, X.L.; Chang, R.D.; Wen, T. Overcoming barriers to off-site construction through engaging stakeholders: A two-mode social network analysis. *J. Clean. Prod.* **2018**, *201*, 735–747. [CrossRef]
35. Alaloul, W.S.; Liew, M.S.; Zawawi, N.A.W.A.; Kennedy, I.B. Industrial Revolution 4.0 in the construction industry: Challenges and opportunities for stakeholders. *Ain Shams Eng. J.* **2020**, *11*, 225–230. [CrossRef]
36. Maskuriy, R.; Selamat, A.; Maresova, P.; Krejcar, O.; David, O.O. Industry 4.0 for the construction industry: Review of management perspective. *Economies* **2019**, *7*, 68. [CrossRef]
37. Cheng, D.; Ma, J. Research on the restrictive factors of the development of Chinese prefabricated buildings. In Proceedings of the 2020 3rd International Conference of Green Buildings and Environmental Management (GBEM), Qingdao, China, 12–14 June 2020.
38. Voordijk, J.T. Technological Mediation in Construction: Postphenomenological Inquiry into Digital Technologies. *J. Constr. Eng. Manag.* **2019**, *145*. [CrossRef]
39. Hofmann, E.; Rüsch, M. Industry 4.0 and the current status as well as future prospects on logistics. *Comput. Ind.* **2017**, *89*, 23–34. [CrossRef]
40. Shirowzhan, S.; Sepasgozar, S.; Zaini, I.; Wang, C. An integrated GIS and Wi-Fi based Locating system for improving construction labor communications. In Proceedings of the 34th International Symposium on Automation and Robotics in Construction, Taipei, Taiwan, 28 June–1 July 2017; pp. 1052–1059.
41. Sepasgozar, S.M. Digital technology utilisation decisions for facilitating the implementation of Industry 4.0 technologies. *Constr. Innov.* **2020**. [CrossRef]
42. Woodhead, R.; Stephenson, P.; Morrey, D. Digital construction: From point solutions to IoT ecosystem. *Autom. Constr.* **2018**, *93*, 35–46. [CrossRef]
43. Li, J.; Greenwood, D.; Kassem, M. Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Autom. Constr.* **2019**, *102*, 288–307. [CrossRef]
44. Andre, L.; Michael, B.; Daniel, R.; Christian, K. Framework for the identification and demand-orientated classification of digital technologies. In Proceedings of the 2018 IEEE International Conference on Technology Management, Operations and Decisions (ICTMOD 2018), Marrakech, Morocco, 21–23 November 2018; pp. 31–36.
45. Leviäkangas, P.; Mok Paik, S.; Moon, S. Keeping up with the pace of digitization: The case of the Australian construction industry. *Technol. Soc.* **2017**, *50*, 33–43. [CrossRef]
46. Yin, X.; Liu, H.; Chen, Y.; Al-Hussein, M. Building information modelling for off-site construction: Review and future directions. *Autom. Constr.* **2019**, *101*, 72–91. [CrossRef]
47. Shirowzhan, S.; Sepasgozar, S.M.E.; Edwards, D.J.; Li, H.; Wang, C. BIM compatibility and its differentiation with interoperability challenges as an innovation factor. *Autom. Constr.* **2020**, *112*, 103086. [CrossRef]
48. Baldini, G.; Desruelle, P.; Bono, F.; Delipetrev, B.; Gkoumas, K.; Sanchez, I.; Pagano, A.; Nepelski, D.; Prettico, G.; Urzi Brancati, C.; et al. *Digital Transformation in Transport, Construction, Energy, Government and Public Administration*; Publications Office of the European Union: Luxembourg, 2019. [CrossRef]
49. Calvetti, D.; Mêda, P.; Gonçalves, M.C.; Sousa, H. Worker 4.0: The future of sensored construction sites. *Buildings* **2020**, *10*, 169. [CrossRef]
50. Borrmann, A.; König, M.; Koch, C.; Beetz, J. *Building Information Modeling: Technology Foundations and Industry Practice*; Springer International Publishing: Berlin/Heidelberg, Germany, 2018; pp. 1–584. [CrossRef]
51. Darko, A.; Chan, A.P.C.; Adabre, M.A.; Edwards, D.J.; Hosseini, M.R.; Ameyaw, E.E. Artificial intelligence in the AEC industry: Scientometric analysis and visualization of research activities. *Autom. Constr.* **2020**, *112*, 103081. [CrossRef]
52. Gimeno, J.; Morillo, P.; Orduña, J.M.; Fernández, M. An occlusion-aware AR authoring tool for assembly and repair tasks. In Proceedings of the International Conference on Computer Graphics Theory and Applications (GRAPP 2012) and International Conference on Information Visualization Theory and Applications (IVAPP 2012), Rome, Italy, 24–26 February 2012; pp. 377–386.
53. Sepasgozaar, S.M.E.; Shirowzhan, S.; Wang, C. A Scanner Technology Acceptance Model for Construction Projects. *Procedia Eng.* **2017**, *180*, 1237–1246. [CrossRef]

54. Jin, R.; Zou, Y.; Gidado, K.; Ashton, P.; Painting, N. Scientometric analysis of BIM-based research in construction engineering and management. *Eng. Constr. Archit. Manag.* **2019**, *26*, 1750–1776. [CrossRef]
55. Akbarieh, A.; Jayasinghe, L.B.; Waldmann, D.; Teferle, F.N. BIM-based end-of-lifecycle decision making and digital deconstruction: Literature review. *Sustainability* **2020**, *12*, 2670. [CrossRef]
56. Alfieri, E.; Seghezzi, E.; Sauchelli, M.; Di Giuda, G.M.; Masera, G. A BIM-based approach for DfMA in building construction: Framework and first results on an Italian case study. *Archit. Eng. Des. Manag.* **2020**. [CrossRef]
57. Gbadamosi, A.Q.; Mahamadu, A.M.; Oyedele, L.O.; Akinade, O.O.; Manu, P.; Mahdjoubi, L.; Aigbavboa, C. Offsite construction: Developing a BIM-Based optimizer for assembly. *J. Clean. Prod.* **2019**, *215*, 1180–1190. [CrossRef]
58. Yuan, Z.; Sun, C.; Wang, Y. Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. *Autom. Constr.* **2018**, *88*, 13–22. [CrossRef]
59. Samarasinghe, T.; Gunawardena, T.; Mendis, P.; Sofi, M.; Aye, L. Dependency Structure Matrix and Hierarchical Clustering based algorithm for optimum module identification in MEP systems. *Autom. Constr.* **2019**, *104*, 153–178. [CrossRef]
60. Han, C.; Ye, H. A novel IoT-Cloud-BIM based intelligent information management system in building industrialization. In Proceedings of the 2018 International Conference on Construction and Real Estate Management: Innovative Technology and Intelligent Construction (ICCREM 2018), Charleston, SC, USA, 9–10 August 2018; pp. 72–77.
61. Vernikos, V.K.; Goodier, C.I.; Broyd, T.W.; Robery, P.C.; Gibb, A.G.F. Building information modelling and its effect on off-site construction in UK civil engineering. *Proc. Inst. Civ. Eng. Manag. Procure. Law* **2014**, *167*, 152–159. [CrossRef]
62. Xu, Z.; Abualdenien, J.; Liu, H.; Kang, R. An IDM-Based Approach for Information Requirement in Prefabricated Construction. *Adv. Civ. Eng.* **2020**, *2020*, 8946530. [CrossRef]
63. Sepasgozar, S.; Huang, T.; Wang, C.; Tahmasebinia, F. Energy optimization in modular buildings made from 3D printing. In Proceedings of the 2017 Modular and Offsite Construction Summit & the 2nd International Symposium on Industrialized Construction Technology, Shanghai, China, 10–12 November 2017.
64. Mao, C.; Tao, X.; Yang, H.; Chen, R.; Liu, G. Real-time carbon emissions monitoring tool for prefabricated construction: An IoT-based system framework. In Proceedings of the 2018 International Conference on Construction and Real Estate Management: Sustainable Construction and Prefabrication (ICCREM 2018), Charleston, SC, USA, 9–10 August 2018; pp. 121–127.
65. Liu, G.; Yang, H.; Fu, Y.; Mao, C.; Xu, P.; Hong, J.; Li, R. Cyber-physical system-based real-time monitoring and visualization of greenhouse gas emissions of prefabricated construction. *J. Clean. Prod.* **2020**, *246*. [CrossRef]
66. Li, Z.; Shen, G.Q.; Xue, X. Critical review of the research on the management of prefabricated construction. *Habitat Int.* **2014**, *43*, 240–249. [CrossRef]
67. Charnwasununth, P.; Yabuki, N.; Tongthong, T. Dynamic information support system for the process of prefabricated member installation using RFID technology and multi-agent system. In Proceedings of the 17th International Workshop on Intelligent Computing in Engineering (EG-ICE 2010), Nottingham, UK, 30 June–2 July 2010.
68. Xu, G.; Li, M.; Chen, C.H.; Wei, Y. Cloud asset-enabled integrated IoT platform for lean prefabricated construction. *Autom. Constr.* **2018**, *93*, 123–134. [CrossRef]
69. Wang, Z.; Hu, H.; Zhou, W. RFID Enabled Knowledge-Based Precast Construction Supply Chain. *Comput. Aided Civ. Infrastruct. Eng.* **2017**, *32*, 499–514. [CrossRef]
70. Wang, C.C.; Chien, O. The use of BIM in project planning and scheduling in the australian construction industry. In Proceedings of the 2014 International Conference on Construction and Real Estate Management: Smart Construction and Management in the Context of New Technology (ICCREM 2014), Kunming, China, 27–28 September 2014; pp. 126–133.
71. Senthilvel, M.; Varghese, K.; Ramesh Babu, N. Building information modeling for precast construction: A review of research and practice. In Proceedings of the Construction Research Congress 2016: Old and New Construction Technologies Converge in Historic San Juan (CRC 2016), San Juan, Puerto Rico, 31 May–2 June 2016; pp. 2250–2259.
72. Garg, A.; Kamat, V.R. Virtual Prototyping for Robotic Fabrication of Rebar Cages in Manufactured Concrete Construction. *J. Archit. Eng.* **2014**, *20*, 06013002. [CrossRef]

73. Krieg, O.D.; Lang, O. Adaptive automation strategies for robotic prefabrication of parametrized mass timber building components. In Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC 2019), Banff, AB, Canada, 21–24 May 2019; pp. 521–528.
74. Naranje, V.; Swarnalatha, R. Design of tracking system for prefabricated building components using RFID technology and CAD model. In Proceedings of the 12th International Conference Interdisciplinarity in Engineering (INTER-ENG 2018), Tirgu Mures, Romania, 4–5 October 2018; pp. 928–935.
75. Liu, H.; Sydora, C.; Altaf, M.S.; Han, S.; Al-Hussein, M. Towards sustainable construction: BIM-enabled design and planning of roof sheathing installation for prefabricated buildings. *J. Clean. Prod.* **2019**, *235*, 1189–1201. [CrossRef]
76. Minunno, R.; O'Grady, T.; Morrison, G.M.; Gruner, R.L.; Colling, M. Strategies for applying the circular economy to prefabricated buildings. *Buildings* **2018**, *8*, 125. [CrossRef]
77. Bataglin, F.S.; Viana, D.D.; Formoso, C.T.; Bulhões, I.R. Model for planning and controlling the delivery and assembly of engineer-to-order prefabricated building systems: Exploring synergies between lean and BIM. *Can. J. Civ. Eng.* **2020**, *47*, 165–177. [CrossRef]
78. Moghadam, M.; Alwisy, A.; Al-Hussein, M. Integrated BIM/Lean base production line schedule model for modular construction manufacturing. In Proceedings of the Construction Research Congress 2012, West Lafayette, IN, USA, 21–23 May 2012; pp. 1271–1280.
79. Xu, Z.; Wang, S.; Wang, E. Integration of BIM and Energy Consumption Modelling for Manufacturing Prefabricated Components: A Case Study in China. *Adv. Civ. Eng.* **2019**, *2019*, 1609523. [CrossRef]
80. Ji, Y.; Chang, S.; Qi, Y.; Li, Y.; Li, H.X.; Qi, K.; Pellicer, E. A BIM-Based Study on the Comprehensive Benefit Analysis for Prefabricated Building Projects in China. *Adv. Civ. Eng.* **2019**, *2019*, 3720191. [CrossRef]
81. Li, D.; Li, X.; Feng, H.; Wang, Y.; Fan, S. ISM-based relationship among critical factors that affect the choice of prefabricated concrete buildings in China. *Int. J. Constr. Manag.* **2019**. [CrossRef]
82. Tan, T.; Chen, K.; Xue, F.; Lu, W. Barriers to Building Information Modeling (BIM) implementation in China's prefabricated construction: An interpretive structural modeling (ISM) approach. *J. Clean. Prod.* **2019**, *219*, 949–959. [CrossRef]
83. Abanda, F.H.; Tah, J.H.M.; Cheung, F.K.T. BIM in off-site manufacturing for buildings. *J. Build. Eng.* **2017**, *14*, 89–102. [CrossRef]
84. Luo, M.; Chen, D. Application of BIM technology in prefabricated building. In Proceedings of the 2018 International Conference on Construction and Real Estate Management: Innovative Technology and Intelligent Construction (ICCREM 2018), Charleston, SC, USA, 9–10 August 2018; pp. 263–270.
85. Zhang, T.; Man, Q. A review of the application of BIM in the assembly construction. In Proceedings of the 2018 International Conference on Construction and Real Estate Management: Innovative Technology and Intelligent Construction (ICCREM 2018), Charleston, SC, USA, 9–10 August 2018; pp. 125–131.
86. Vilutiene, T.; Kalibatiene, D.; Hosseini, M.R.; Pellicer, E.; Zavadskas, E.K. Building information modeling (BIM) for structural engineering: A bibliometric analysis of the literature. *Adv. Civ. Eng.* **2019**, *2019*, 5290690. [CrossRef]
87. Liu, G.; Nzige, J.H.; Li, K. Trending topics and themes in offsite construction(OSC) research: The application of topic modelling. *Constr. Innov.* **2019**, *19*, 343–366. [CrossRef]
88. Sepasgozar, S.M.E.; Costin, A.; Wang, C. Challenges of migrating from desktop-based BIM in construction. In Proceedings of the 33th International Symposium on Automation and Robotics in Construction, Auburn, AL, USA, 18–21 July 2016; pp. 934–942.
89. Zhao, P.A.; Wang, C.C. A comparison of using traditional cost estimating software and BIM for construction cost control. In Proceedings of the ICCREM 2014, Kunming, China, 27–28 September 2014; pp. 256–264.
90. Singh, M.M.; Sawhney, A.; Borrmann, A. Integrating rules of modular coordination to improve model authoring in BIM. *Int. J. Constr. Manag.* **2019**, *19*, 15–31. [CrossRef]
91. Brown, R.; Barkokebas, B.; Ritter, C.; Al-Hussein, M. Predicting performance indicators using BIM and simulation for a wall assembly line. In Proceedings of the 27th Annual Conference of the International Group for Lean Construction (IGLC 2019), Dublin, Ireland, 3–5 July 2019; pp. 853–862.
92. Ramaji, I.J.; Memari, A.M. Information exchange standardization for BIM application to multi-story modular residential buildings. In Proceedings of the Architectural Engineering National Conference 2015: Birth and Life of the Integrated Building (AEI 2015), Milwaukee, WI, USA, 24–27 March 2015; pp. 13–24.

93. Ramaji, I.J.; Memari, A.M. Extending the current model view definition standards to support multi-storey modular building projects. *Archit. Eng. Des. Manag.* **2018**, *14*, 158–176. [CrossRef]
94. Ramaji, I.J.; Memari, A.M.; Messner, J.I. Product-Oriented Information Delivery Framework for Multistory Modular Building Projects. *J. Comput. Civ. Eng.* **2017**, *31*. [CrossRef]
95. Sharma, S.; Sawhney, A.; Arif, M. Parametric modelling for designing offsite construction. In Proceedings of the Creative Construction Conference (CCC 2017), Primosten, Croatia, 19–22 June 2017; pp. 1114–1121.
96. Zhong, R.Y.; Peng, Y.; Xue, F.; Fang, J.; Zou, W.; Luo, H.; Thomas Ng, S.; Lu, W.; Shen, G.Q.P.; Huang, G.Q. Prefabricated construction enabled by the Internet-of-Things. *Autom. Constr.* **2017**, *76*, 59–70. [CrossRef]
97. Zhai, Y.; Chen, K.; Zhou, J.X.; Cao, J.; Lyu, Z.; Jin, X.; Shen, G.Q.P.; Lu, W.; Huang, G.Q. An Internet of Things-enabled BIM platform for modular integrated construction: A case study in Hong Kong. *Adv. Eng. Inform.* **2019**, *42*, 100997. [CrossRef]
98. Ke, C.; Gangyan, X.; Fan, X.; Zhong, R.Y.; Diandian, L.; Weisheng, L. A physical internet-enabled building information modelling system for prefabricated construction. *Int. J. Comput. Integr. Manuf.* **2018**, *31*, 349–361. [CrossRef]
99. Sun, S.; Ge, J. Research on risk evaluation of BIM application in prefabricated buildings. In Proceedings of the 7th International Symposium on Project Management (ISPM 2019), Chongqing, China, 6 July 2019; pp. 600–606.
100. Wang, J.; Yin, X.; Tian, Y.; Li, X.; Al-Hussein, M. Simulation of production line improvements in panelised floor manufacturing. In Proceedings of the 30th European Modeling and Simulation Symposium (EMSS 2018), Budapest, Hungary, 17–19 September 2018; pp. 157–164.
101. Li, C.Z.; Hong, J.; Xue, F.; Shen, G.Q.; Xu, X.; Mok, M.K. Schedule risks in prefabrication housing production in Hong Kong: A social network analysis. *J. Clean. Prod.* **2016**, *134*, 482–494. [CrossRef]
102. Altaf, M.S.; Bouferguene, A.; Liu, H.; Al-Hussein, M.; Yu, H. Integrated production planning and control system for a panelized home prefabrication facility using simulation and RFID. *Autom. Constr.* **2018**, *85*, 369–383. [CrossRef]
103. Li, C.Z.; Zhong, R.Y.; Xue, F.; Xu, G.; Chen, K.; Huang, G.G.; Shen, G.Q. Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction. *J. Clean. Prod.* **2017**, *165*, 1048–1062. [CrossRef]
104. Bortolini, R.; Formoso, C.T.; Viana, D.D. Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling. *Autom. Constr.* **2019**, *98*, 248–264. [CrossRef]
105. Xu, G.; Li, M.; Luo, L.; Chen, C.H.; Huang, G.Q. Cloud-based fleet management for prefabrication transportation. *Enterp. Inf. Syst.* **2019**, *13*, 87–106. [CrossRef]
106. Qi, B.; Chen, K.; Costin, A. RFID and BIM-enabled prefabricated component management system in prefabricated housing production. In Proceedings of the Construction Research Congress 2018: Construction Information Technology (CRC 2018), New Orleans, LA, USA, 2–4 April 2018; pp. 591–601.
107. Zeng, N.; Dichtl, M.; Konig, M. A scenario-based simulation framework of on- and off-site construction logistics. In Proceedings of the 2017 Winter Simulation Conference (WSC 2017), Crystal City, VA, USA, 3–6 December 2017; pp. 2348–2359.
108. Tang, X.; Chong, H.Y.; Zhang, W. Relationship between BIM Implementation and Performance of OSM Projects. *J. Manag. Eng.* **2019**, *35*. [CrossRef]
109. Jia, M.; Komeily, A.; Wang, Y.; Srinivasan, R.S. Adopting Internet of Things for the development of smart buildings: A review of enabling technologies and applications. *Autom. Constr.* **2019**, *101*, 111–126. [CrossRef]
110. Li, X.; Shen, G.Q.; Wu, P.; Fan, H.; Wu, H.; Teng, Y. RBL-PHP: Simulation of Lean Construction and Information Technologies for Prefabrication Housing Production. *J. Manag. Eng.* **2018**, *34*. [CrossRef]
111. Ritter, C.; Abaeian, H.; Sirbu, V.; Al-Hussein, M. Radio-frequency identification based process management for production line balancing. In Proceedings of the 35th International Symposium on Automation and Robotics in Construction and International AEC/FM Hackathon: The Future of Building Things (ISARC 2018), Berlin, Germany, 20–25 July 2018.
112. Li, X.; Chi, H.L.; Wu, P.; Shen, G.Q. Smart work packaging-enabled constraint-free path re-planning for tower crane in prefabricated products assembly process. *Adv. Eng. Inform.* **2020**, *43*. [CrossRef]
113. Kang, J.; Ganapathi, A.; Lee, J.; Faghihi, V. BIM to field: Robotic total station and BIM for quality control. In Proceedings of the European Conference on Product and Process Modelling (ECPPM 2012), Reykjavik, Iceland, 25–27 July 2012; pp. 717–722.

114. Ahn, S.; Han, S.; Al-Hussein, M. Improvement of transportation cost estimation for prefabricated construction using geo-fence-based large-scale GPS data feature extraction and support vector regression. *Adv. Eng. Inform.* **2020**, *43*. [CrossRef]
115. Li, C.Z.; Hong, J.; Xue, F.; Shen, G.Q.; Xu, X.; Luo, L. SWOT analysis and Internet of Things-enabled platform for prefabrication housing production in Hong Kong. *Habitat Int.* **2016**, *57*, 74–87. [CrossRef]
116. Zhai, Y.; Chen, K.; Zhou, J.X.; Cao, J.; Lyu, Z.; Jin, X.; Fang, X.; Zhong, R.Y.; Shen, G.Q.P.; Lu, W.; et al. An internet of things-enabled BIM platform for modular integrated construction. In Proceedings of the 48th International Conference on Computers and Industrial Engineering (CIE 2018), Auckland, New Zealand, 2–5 December 2018.
117. Valinejadshoubi, M.; Bagchi, A.; Moselhi, O. Development of a BIM-Based Data Management System for Structural Health Monitoring with Application to Modular Buildings: Case Study. *J. Comput. Civ. Eng.* **2019**, *33*, 05019003. [CrossRef]
118. García-Pereira, I.; Portalés, C.; Gimeno, J.; Casas, S. A collaborative augmented reality annotation tool for the inspection of prefabricated buildings. *Multimed Tools Appl.* **2020**, *79*, 6483–6501. [CrossRef]
119. Zhou, Y.; Luo, H.; Yang, Y. Implementation of augmented reality for segment displacement inspection during tunneling construction. *Autom. Constr.* **2017**, *82*, 112–121. [CrossRef]
120. Raimbaud, P.; Lou, R.; Merienne, F.; Danglade, F.; Figueroa, P.; Hernandez, J.T. BIM-based mixed reality application for supervision of construction. In Proceedings of the 26th IEEE Conference on Virtual Reality and 3D User Interfaces (VR 2019), Osaka, Japan, 23–27 March 2019; pp. 1903–1907.
121. Goh, J.; Hu, S.; Fang, Y. Human-in-the-loop simulation for crane lift planning in modular construction on-site assembly. In Proceedings of the ASCE International Conference on Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation (i3CE 2019), Atlanta, GA, USA, 17–19 June 2019; pp. 71–78.
122. Zhang, Z.; Pan, W. Virtual reality (Vr) supported lift planning for modular integrated construction (mic) of high-rise buildings. *Hong Kong Inst. Eng. Trans.* **2019**, *26*, 136–143. [CrossRef]
123. Martinez, P.; Ahmad, R.; Al-Hussein, M. A vision-based system for pre-inspection of steel frame manufacturing. *Autom. Constr.* **2019**, *97*, 151–163. [CrossRef]
124. Li, X.; Chi, H.L.; Zhang, W.F.; Shen, G.Q. Monitoring and alerting of crane operator fatigue using hybrid deep neural networks in the prefabricated products assembly process. In Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC 2019), Banff, AB, Canada, 21–24 May 2019; pp. 680–687.
125. Guo, J.; Wang, Q.; Park, J.H. Geometric quality inspection of prefabricated MEP modules with 3D laser scanning. *Autom. Constr.* **2020**, *111*. [CrossRef]
126. Sepasgozar, S.M.; Forsythe, P.; Shirowzhan, S. Evaluation of terrestrial and mobile scanner technologies for part-built information modeling. *J. Constr. Eng. Manag.* **2018**, *144*, 04018110. [CrossRef]
127. Shirowzhan, S.; Sepasgozar, S.M. Spatial analysis using temporal point clouds in advanced GIS: Methods for ground elevation extraction in slant areas and building classifications. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 120. [CrossRef]
128. Arashpour, M.; Heidarpour, A.; Akbar Nezhad, A.; Hosseinifard, Z.; Chileshe, N.; Hosseini, R. Performance-based control of variability and tolerance in off-site manufacture and assembly: Optimization of penalty on poor production quality. *Constr. Manag. Econ.* **2020**, *38*, 502–514. [CrossRef]
129. Kalasapudi, V.S.; Tang, P. Automated tolerance analysis of curvilinear components using 3D point clouds for adaptive construction quality control. In Proceedings of the 2015 ASCE International Workshop on Computing in Civil Engineering (IWCCE 2015), Austin, TX, USA, 21–23 June 2015; pp. 57–65.
130. Chai, J.; Chi, H.-L.; Wang, X.; Wu, C.; Jung, K.H.; Lee, J.M. Automatic as-built modeling for concurrent progress tracking of plant construction based on laser scanning. *Concurr. Eng.* **2016**, *24*, 369–380. [CrossRef]
131. Zhang, C.; Arditi, D. Automated progress control using laser scanning technology. *Autom. Constr.* **2013**, *36*, 108–116. [CrossRef]
132. Che, E.; Jung, J.; Olsen, M.J. Object recognition, segmentation, and classification of mobile laser scanning point clouds: A state of the art review. *Sensors* **2019**, *19*, 810. [CrossRef] [PubMed]
133. Shirowzhan, S.; Sepasgozar, S.M.; Li, H.; Trinder, J.; Tang, P. Comparative analysis of machine learning and point-based algorithms for detecting 3D changes in buildings over time using bi-temporal lidar data. *Autom. Constr.* **2019**, *105*, 102841. [CrossRef]

134. Sepasgozar, S.M.E.; Lim, S.; Shirowzhan, S.; Kim, Y.M. Implementation of As-Built Information Modelling Using Mobile and Terrestrial Lidar Systems. In Proceedings of the 31st International Symposium on Automation and Robotics in Construction and Mining (ISARC 2014), Sydney, Australia, 9–11 July 2014.
135. Sepasgozar, S.M.E.; Wang, C.C.; Shirowzhan, S. Challenges and opportunities for implementation of laser scanners in building construction. In Proceedings of the 33rd International Symposium on Automation and Robotics in Construction (ISARC 2016), Auburn, AL, USA, 18–21 July 2016; pp. 742–751.
136. Baghdadi, A.; Heristchian, M.; Kloft, H. Design of prefabricated wall-floor building systems using meta-heuristic optimization algorithms. *Autom. Constr.* **2020**, *114*. [CrossRef]
137. Hamdan, S.B.; Alwisy, A.; Al-Hussein, M.; Abourizk, S.; Ajweh, Z. Simulation based multi-objective cost-time trade-off for multi-family residential off-site construction. In Proceedings of the Winter Simulation Conference (WSC 2015), Huntington Beach, CA, USA, 6–9 December 2015; pp. 3391–3401.
138. Daget, Y.T.; Zhang, H. Decision-making model for the evaluation of industrialized housing systems in Ethiopia. *Eng. Constr. Archit. Manag.* **2019**, *27*, 296–320. [CrossRef]
139. Arashpour, M.; Bai, Y.; Aranda-mena, G.; Bab-Hadiashar, A.; Hosseini, R.; Kalutara, P. Optimizing decisions in advanced manufacturing of prefabricated products: Theorizing supply chain configurations in off-site construction. *Autom. Constr.* **2017**, *84*, 146–153. [CrossRef]
140. Zhu, L.; Meng, X.; Shi, Z.; Huang, Y. Selection of prefabricated concrete factories' location based on triangular fuzzy numbers and fuzzy group decision-making. In Proceedings of the 3rd International Conference on Computational Intelligence and Applications (ICCIA 2018), Hong Kong, China, 28–30 July 2018; pp. 26–30.
141. Han, D.; Yin, H.; Qu, M.; Zhu, J.; Wickes, A. Technical Analysis and Comparison of Formwork-Making Methods for Customized Prefabricated Buildings: 3D Printing and Conventional Methods. *J. Archit. Eng.* **2020**, *26*. [CrossRef]
142. Yang, H.; Chung, J.K.H.; Chen, Y.; Li, Y. The cost calculation method of construction 3D printing aligned with internet of things. *EURASIP J. Wirel. Commun. Netw.* **2018**, *2018*, 147. [CrossRef]
143. Pan, M.; Pan, W. Determinants of Adoption of Robotics in Precast Concrete Production for Buildings. *J. Manag. Eng.* **2019**, *35*. [CrossRef]
144. Han, Z.; Wang, Y. The applied exploration of big data technology in prefabricated construction project management. In Proceedings of the 2017 International Conference on Construction and Real Estate Management: Prefabricated Buildings, Industrialized Construction, and Public-Private Partnerships (ICCREM 2017), Guangzhou, China, 10–12 November 2017; pp. 71–78.
145. Wang, Z.; Wang, T.; Hu, H.; Gong, J.; Ren, X.; Xiao, Q. Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. *Autom. Constr.* **2020**, *111*, 103063. [CrossRef]
146. Maskuriy, R.; Selamat, A.; Ali, K.; Maresova, P.; Krejcar, O. Industry 4.0 for the Construction Industry—How Ready Is the Industry? *Appl. Sci.* **2019**, *9*, 2819. [CrossRef]

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