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Modelling in Off-Site Construction Supply Chain Management: A Review and Future Directions for Sustainable Modular Integrated Construction

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Abstract

Off-site construction (OSC) is an innovative and sustainable construction method. One of its critical success factors is the proper management of its supply chain (SC). Recently, significant research attention has been focused on the modelling of OSC-SC to improve its performance and sustainability. However, the literature still lacks a comprehensive review of the modelling studies on off-site construction -supply chain management (OSC-SCM). Therefore, this research contributes by providing a comprehensive and up-to-date mapping and clustering of 309 journal articles on the modelling of OSC-SC to identify its trends and gaps, and hence, highlight future research opportunities. To achieve these objectives, a mixed review method, consisting of scientometric and systematic reviews, is used. The scientometric review identifies the most prolific journals, researchers, co-occurrence network of keywords, and their citation bursts. On the other hand, the systematic review classifies the articles based on OSC type and supply chain (SC) stage. At each SC stage, the articles are further classified based on problem settings and solution methods. The results show that production problems have received the most attention (i.e., by 28% of the included articles), followed by on-site construction (19%), design (13%), and logistics (7%) problems. However, researchers are more inclined to address problems at multiple SC stages (33%) due to the interrelationship between these stages. Besides, the systematic analysis shows that OSC-SC problems have been solved frequently by a variety of solution methods such as optimization (25%), simulation (13%) and building information modelling (BIM) (9.5%). However, researchers tend more to integrate multiple solution methods (35%) to address the complexities of OSC-SC problems. Finally, the included studies are classified based on the three sustainability dimensions. The results show that economic, environmental, and social sustainability dimensions have been considered in previous studies by 72%, 24%, and 4%, respectively. Therefore, the study identifies research gaps at each SC stage of each OSC type to incentivize future studies to consider more environmental and social sustainability factors in OSC-SC models. Since modular integrated construction (MiC) has the highest prefabrication level, this study provides future research directions for sustainable supply chain management (SCM) in MiC. The present research is an important reference guide that helps researchers and practitioners to understand different problem settings and their solution methods in OSC-SCM.

Keywords: Supply chain management; Logistics; Sustainability; Modelling; Literature review;

Modular integrated construction.

1. INTRODUCTION

Off-site construction (OSC) is an innovative construction method of dividing a whole structure into a number of prefabricated sections produced in a factory environment and transported to the construction site for direct installation (Jin et al., 2018). These sections can be prefabricated components (PCs) (e.g., beams, columns, slabs, stairs, etc.), panelized elements, or full-volumetric modules (Innella et al., 2019). Indeed, they can be made from different materials, such as concrete, steel, timber, and composites for both buildings (e.g., houses, schools, hospitals, etc.) and infrastructure projects (e.g., bridges and tunnels). OSC offers some advantages over the traditional construction method. These include faster construction (Heravi et al., 2019), lower construction wastes (Wang et al., 2015), higher quality (Tam et al., 2015), higher safety (Fard et al., 2017) and more sustainability (Monahan and Powell, 2011).

Despite these advantages, OSC brings some challenges to the construction industry. Off-site construction-supply chain management (OSC-SCM) is a key challenge to the successful delivery of OSC projects (Wang et al., 2018c). This is due to the higher complexity and fragmentation of the off-site construction-supply chain (OSC-SC) compared to the supply chain (SC) of the traditional cast-in-situ construction (Wang et al., 2019). The OSC-SC is a multi-echelon supply chain starting from preparing detailed design and shop drawings of structure's components to be manufactured in a prefabricated facility. Then, these components are stored and transported to construction sites for installation. These components are customized to suit each project's specifications. Thus, prefabricators cannot produce these components before receiving orders. Also, as these components are heavy and bulky, contractors cannot hold large buffer stocks of them to hedge against any delivery delays (Hsu et al., 2018). Besides, the OSC-SC abounds with risks distributed along its stages (i.e., design, production, logistics, and on-site construction) (Wang et al., 2018c). Any disruption which occurs at the top of the OSC-SC affects the subsequent stages, resulting in an inefficient SC. Therefore, researchers have resorted to various modelling methods to study the OSC-SC and improve its performance and sustainability. For instance, Hsu et al. (2019) have developed a robust optimization model to find the optimal production and logistics decisions that enhanced economic sustainability by reducing SC costs. Ji et al. (2018) have conducted a cradle to site life cycle assessment (LCA) to estimate greenhouse gas

(GHG) emissions generated from using the precast-in-situ construction method. Jeong et al. (2017) have applied discrete-event simulation (DES) to estimate the SC's cost, productivity, and CO_2 emissions. Using a building information modelling (BIM) model, Ding et al. (2020) have developed a carbon emission measurement system for the prefabricated SC. Shi et al. (2018) have developed a game theory model to design a win-win incentive mechanism to improve PCs' quality, productivity, and sustainability. To enhance social sustainability for workers, Golabchi et al. (2016) have proposed a fuzzy logic-based approach for on-site ergonomic assessment. These methods have been used to address managerial and operational problems at each stage of SC and improve its performance and sustainability. However, a conscious effort is needed to integrate and classify the existing literature on the modelling of OSC-SC. This will provide a better understanding of this discipline and create a comprehensive reference for future researchers.

The increasing growth of studies on OSC has recently motivated some researchers to conduct review articles on the topic. For instance, Li et al. (2014) have conducted a scientometric review of 100 articles focusing on management issues in prefabricated construction. Later, Jin et al. (2018) have conducted a more comprehensive scientometric review on 349 articles to understand the network of keywords and collaboration networks between research outlets, researchers, and countries. They have also provided a qualitative analysis of key research areas on OSC identified from using the analysis of keywords. Liu et al. (2019) have applied a topic-modelling approach to 1,057 documents on OSC to identify research topics and themes while eliminating subjective judgment. To focus more on the OSC-SCM, Liu et al. (2020) have conducted a scientometric review of 152 articles and qualitatively discussed them to identify the trends and gaps in the research domain of OSC-SCM. The study classified the included articles into four research themes identified from the scientometric analysis. These themes are SC strategic management, SC integration and management, SC design and optimization, and SC advanced technology. Although this classification has provided an overview of the research topics in OSC-SCM and the methodologies and technologies applied in this domain, it has not provided an understanding of the different tactical and operational problems addressed in each SC stage and their interrelationships, and how researchers solved them. Also, the review studies mentioned above have not included articles on the design stage and the SC of prefabricated infrastructure. Despite the contributions of these review studies, they are not dedicated to the modelling of OSC-SC. Besides, they lack an in-depth systematic analysis to understand modelling methods and problem settings in the field of OSC-SCM along its four stages (i.e., design, production, logistics and installation stages). Wang et al. (2019) have covered this gap partially by conducting a mixed review, including scientometric and systematic reviews of 103 articles. They provide an in-depth analysis of the modelling methods and problem settings of the included articles. However, these articles are limited to the production and logistics stages of precast components without considering the design and on-site construction stages, albeit their imperative importance to the sustainability of OSC-SC. Also, other types of OSC, such as panelized construction, modular integrated construction (MiC), and construction-based PCs made from materials other than concrete, have not been included. Furthermore, due to the continuous growth of research on the modelling of OSC-SCM, 152 new studies on the modelling of OSC-SC have been conducted after the study by Wang et al. (2019). Therefore, by conducting an extensive overview of 309 articles dedicated to the modelling of OSC-SC, the novelty of this current research is to provide a more comprehensive, structured and up-to-date review of the modelling methods and problem settings in OSC-SCM covering all of OSC types and its SC stages.

This study deploys a mixed review method to provide a holistic science mapping and a classification of OSC-SCM based on OSC type, problem sets, and solution method. This method is chosen to combine the merits of both the scientometric and systematic review methods. Firstly, a scientometric review is conducted to: 1) find the high impact journals; 2) identify the active researchers; 3) retrieve the highly cited articles; and 4) identify the co-occurrence network of keywords and their citation bursts. This reveals the research themes covered in the modelling of OSC-SC and potential research areas for future research. Secondly, a systematic review is implemented to: 1) classify the included articles based on OSC types and SC stages; 2) identify solution methods and problem settings of each SC stage of different OSC types; 3) classify the included articles based on their consideration of the three sustainability dimensions (i.e., economic, environmental, and social) and 4) identify specific research gaps at each SC stage for individual OSC type. With these objectives, researchers and practitioners can easily identify the research frontiers in OSC-SC modelling.

The rest of the paper is organized as follows. Section 2 illustrates the methods used to extract the relevant articles on the modelling of OSC-SC and the mixed review method. Section 3 discusses the scientometric analysis results, while section 4 provides a systematic analysis of the included studies. Then, section 5 offers future research directions in the modelling of OSC-SC. Finally, conclusions and research limitations are discussed in section 6.

2. METHODOLOGY

Fig. 1 shows an outline of the research methodology. This methodology consists of two consecutive steps. The first step extracts modelling studies on the OSC-SCM and evaluates them to obtain the relevant studies. In the second step, a mixed review method is utilized to provide an in-depth understanding of the OSC-SC models, and hence, to identify research gaps and future research directions. The following sections illustrate how these steps are performed.

Fig. 1

2.1 Extraction and Evaluation of Bibliometric Data

This step comprises four processes, of which the first is to search the databases. Since the Scopus database has a broader coverage of scientific publications than the other databases (Darko et al., 2020), it has been used to extract the modelling studies on OSC-SCM. Then, a comprehensive list of relevant and alternative keywords related to both the off-site construction (e.g., prefabricated construction, panelized construction, and modular construction) and the different stages of its SC (design, production, logistics, installation, and supply chain) is used to extract the bibliometric data. The third process is to identify inclusion and exclusion criteria to refine the retrieved studies and keep the relevant ones. In this study, the inclusion criteria include: 1) studies that address OSC-SCM problems by using quantitative models; and 2) studies published in journals. Conversely, the exclusion criteria are: 1) studies on the mechanical behaviour of new designs in OSC with minimal consideration to the OSC-SC; 2) studies published in languages other than the English language; and 3) studies without available full text. Since volumetric OSC dated back to the 1970s (Abdelmageed and Zayed, 2020), it would be interesting to consider the research questions raised by the early researchers in this domain. With the tremendous computing resources available these days, new modelling methods could be feasible to address these abandoned yet critical questions. Therefore, there are no restrictions on the publication date of articles. Finally, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol is adopted to evaluate and screen the retrieved studies (Moher et al., 2009). Fig. 2 shows the PRISMA flow diagram, which consists of three sequential stages. First, relevant keywords are deployed to search the Scopus database. As of January 2021, 12145 studies have been identified. Next, the title and abstract of the retrieved studies are screened, which exclude 11440 studies. In the third stage, the full text of each included article (i.e., 12145 - 11440 = 705 studies) is evaluated. Eventually, 309 studies satisfy the inclusion and exclusion criteria, as shown in Fig. 2. These studies are later subjected to the mixed review method.

Fig. 2

2.2 Mixed-review Method

The mixed-review method comprises both the scientometric and systematic review methods. Many researchers have adopted the mixed-review method due to its ability to provide an in-depth understanding of a topic under study using the systematic review method while eliminating biased and subjective conclusions using the analysis of co-occurred keywords and their citation bursts in the scientometric review method (Tariq et al., 2021). Moreover, the advantages of both review methods could be harnessed, while any paradox or contradictions in their findings could be discerned by comparing the results of the two review methods (Johnson and Onwuegbuzie, 2004).

2.2.1 Scientometric review

The scientometric review is a science mapping approach used to visualize networks and relationships among co-occurred keywords, studies, collaborative researchers, journals, institutions, and countries related to a specific research topic. In addition, text mining techniques have eliminated the subjectivity inherent in the findings of narrative and systematic reviews (Hofmann, 2016). Therefore, many studies have applied the scientometric review to various research topics, such as the management of prefabricated construction (Li et al., 2014) and artificial intelligence (AI) applications in the construction industry (Darko et al., 2020).

After obtaining the studies that met the inclusion and exclusion criteria, science mapping software are selected, as the first step, in the scientometric review, as shown in Fig. 1(a). VOSviewer (VanEck and Waltman, 2010) and CiteSpace (Chen, 2006) software are used in this study to analyze the 309 studies obtained from the data extraction and evaluation step illustrated in section 2.1. VOSviewer is used to visualize and analyze the co-occurrence network of keywords, journals, and researchers, while CiteSpace is applied to conduct a citation burst analysis of keywords.

2.2.2 Systematic review

Despite the merits of the scientometric review, it cannot provide a deep understanding of the bibliometric data. Conversely, a systematic review can be deployed to classify the included articles based on OSC types, SC stages, and the three sustainability dimensions. Also, it can be used to identify the types of research problems related to OSC-SCM and which solution methods have been applied. Hence, key research gaps and future research directions can be highlighted. Many researchers have adopted the systematic review method, such as Wang et al. (2019) and Liu et al. (2020).

As shown in Fig. 1(b), the first process to conduct a systematic review is to extract the required data from the included studies (i.e., 309 studies identified in section 2.1) to achieve the objectives of using the systematic review mentioned in section 1. The first objective is to provide a three-dimensional classification of the included studies. This classification is based on OSC types, SC stages, and solution methods constituting a three-dimensional matrix, as shown in Fig. 3. Each element of this matrix represents the number of studies addressing a specific SC stage related to one of the OSC types using a particular solution method. The second objective is to identify the sustainability dimensions considered in these studies. Therefore, these four types of information (i.e., OSC types, SC stages, solution methods and sustainability dimensions) are extracted from the included studies by reading at least their introduction, background, methodology and conclusions. Based on this classification, research gaps are secondly identified for future research consideration.

Fig. 3

3. RESULTS AND DISCUSSION OF SCIENTOMETRIC REVIEW FOR OSC-SCM

This section discusses the scientometric results of the annual publication trend, contributions of journals and researchers, publication co-citation analysis, and keywords-based analysis.

3.1 Annual Publication Trend of Papers in OSC-SCM

Fig. 4 shows the annual number of publications on OSC-SCM over the last four decades. The third-degree polynomial trend line suggests a fast-growing trend in the development and accumulation of knowledge on OSC-SC modelling. Further, this trend indicates that considerable research attention has been devoted to the modelling of OSC-SC, especially during the last two decades. Before this period (between 1980 and 2000), less than one paper is published on OSC-SCM per year, which is attributable to the early stages in the development of OSC-SCM (Liu et al., 2020). However, the average number of modelling studies reaches about fifteen studies annually during the last two decades (from 2001 to 2021). An all-time peak of 52 publications is observed in 2019. Despite the overall gradual increase in research publications, some specific years record a decline in the number of modelling studies. Nonetheless, the expansion of modelling research on OSC-SCM demonstrates that efficient SCM is imperative for the successful delivery of OSC projects.

Fig. 4

3.2 Analysis of Journals Contributing to the Modelling of OSC-SC

Identification of the high impact journals, which publish modelling studies on OSC-SCM, is essential to guide researchers to relevant outlets for their works (Darko et al., 2020). Also, it helps libraries with limited resources to subscribe to key journals on OSC-SCM. Table 1 shows the top scientific journals that publish in this field. These journals have published at least five studies and achieved at least ten citations. These conditions are entered into the VOSviewer software to generate Table 1. Table 1 ranks top journals on OSC-SCM according to several criteria. These criteria are the number of studies, total citations, normalized citations, and total link strength. The normalized citations metric represents the total normalized number of citations received by all the studies published by a journal (van Eck and Waltman, 2013). Normalization corrects for the fact that older studies have a better chance to be cited than more recent studies. The total link strength reflects the total strength of the citation links of a given journal with other journals. The results show that *Automation in Construction* is the most prolific journal in terms of the four metrics (i.e., the number of studies, total citations, normalized citations and total link strength). Following closely are *Journal of Cleaner Production* and *Journal of Construction Engineering and Management.* The subject areas of the journals listed in Table 1 are related to SCM, construction management, operations research, simulation and sustainability. These journals are the best outlets for researchers to publish modelling studies on OSC-SCM.

Table 1

3.3 Active Researchers in the Modelling of OSC-SC

Identification of active researchers in the modelling of OSC-SC promotes collaboration among scholars and helps in knowledge sharing (Hussein and Zayed, 2020a). Co-authorship analysis is done in VOSviewer, by setting the “minimum number of documents of an author” and the “minimum number of citations of an author” to “5” and “90”, respectively. Twenty out of 549 researchers meet these conditions and are listed in Table 2. Table 2 reflects these researchers' contributions in terms of four performance metrics: the number of studies, total citations, normalized citations, and total link strength. In addition, Table 2 ranks the top researchers based on the number of studies. The top five highly cited researchers are Al-Hussein M., Xue F., Hu H., Shen G.Q. and Li C.Z. However, normalization of citations changes this ranking to: Al-Hussein M., Hu H., Arashpour M., Wang Z., and Xue F. The five most collaborative researchers in terms of the total link strength are Shen G.Q., Li C.Z., Xue F., Hermann U., and Taghaddos H.

Table 2

3.4 Article Citation Analysis

This section provides the citation network of the top-cited articles on the modelling of OSC-SC. By setting “the minimum number of citations of a document” to “20”, 86 out of 309 articles meet the condition. Fig. 5 shows the density map of these articles generated by VOSviewer. However, Table 3 summarizes the total number of citations, the number of links, and the normalized number of citations received by the ten top-cited studies. The publication year of these articles ranges from 2007 to 2017. The five most cited articles are studies by Monahan and Powell (2011), Ergen et al. (2007a), Mao et al.

(2013), Garrido et al. (2008), and Jeong et al. (2009). These five studies have addressed various problems in the different stages of OSC-SC. For example, Ergen et al. (2007a) and Yin et al. (2009) have applied positioning and tracking systems (PTS) (e.g., radio frequency identification (RFID) and global positioning system (GPS)) to track PCs during the production and logistics stages. Garrido et al. (2008) have proposed an approach to control the swinging of MiC modules during the on-site installation stage. Besides, Monahan and Powell (2011) and Mao et al. (2013) have studied the environmental impact of different stages of OSC SC. Also, the high number of citations received by the studies of Jeong et al. (2009) and Sacks et al. (2010) signifies the importance of addressing BIM interoperability issues in the design stage of OSC. As shown in Table 3, the normalized citations metric highlights the contribution of a recent study by Zhong et al. (2017). They have proposed an internet-of-things (IoT) approach to enhance OSC-SC performance through real-time information sharing between its different stages. The proposed IoT approach collects real-time information from BIM models and PTS, such as RFID and GPS. This explains the closeness of this study with those of Ergen et al. (2007a), Yin et al. (2009) and Jeong et al. (2009) in the density map shown in Fig. 5. Consequently, it is expected that IoT technology will continue playing a critical role in the improvement of the performance and sustainability of OSC-SC (Liu et al., 2020).

Fig. 5

Table 3

3.5 Keywords Analysis

Keywords analysis shows the co-occurrence network of keywords and their citation burst analysis. The former maps the keywords associated with the modelling studies on OSC-SCM, while the latter highlights hot topics with recent high citations (Chen, 2014)**.**

3.5.1 Co-occurrence network of keywords

The co-occurrence network of keywords provides a mental map of research interests associated with a specific research area and how they are connected. Also, it helps researchers to identify research problems and the solution methods applied to them. Consequently, such networks help researchers to pick some research gaps. The network shown in Fig. 6 is built with 95 keywords obtained by setting "the minimum number of occurrences of a keyword" to "6". In Fig. 6, each node represents a keyword, and its size indicates the number of studies in which the keyword occurs. Besides, the thickness of a line between two keywords reflects the number of times they are mentioned together. The following are the findings from the analysis of the co-occurrence network of keywords shown in Fig. 6:

Fig. 6

1- Regarding the types of off-site construction, the keyword "precast construction" (56 occurrences) is mentioned more than "modular construction" (43 occurrences). Figs. 7(a) and 7(b) show the most frequent keywords, which co-occurred with "modular construction" and "precast construction", respectively. Fig. 7(a) demonstrates that "modular construction" is linked with the different stages of the SC (i.e., design, production, logistics, and on-site construction). The link strengths between "modular construction" and "architectural design", "manufacturing", "logistics", and "cranes" are 5, 9, 3 and 8, respectively. The keyword "cranes" represents the on-site construction stage, as cranes are the key resource in modular construction projects (Lei et al., 2013). These link strengths indicate that the logistics stage in the modular construction SC has received the least attention in the literature. In Fig. 7(b), "precast construction" is linked to "supply chain management", "architectural design", and "logistics", with link strengths of 10, 4, and 3, respectively. Similarly, these results call for more studies on the logistics stage of precast construction. On the contrary, "precast construction" is connected with many keywords related to the production stage. For example, its link strength with "production control", "precast production", "production scheduling", and "manufacturing" are 11, 8, 7, and 6, respectively. This indicates that many studies have addressed different production problems of precast construction.

2- For the types of construction projects, housing projects are dominant, where the keyword "housing" is mentioned 35 times. However, infrastructure projects represented by the keyword "bridges" is repeated eight times, indicating that fewer studies on the SC of off-site infrastructure have been conducted.

3- Figs. 7(c), 7(d), 7(e), and 7(f) show the keyword networks of “supply chain management”, “manufacturing”, “architectural design”, and “logistics”, respectively. These four keywords represent the four stages of the OSC-SCM. “supply chain management” is mentioned in studies that address the whole supply chain. However, the on-site construction stage is not shown here because many keywords could represent this stage, such as “construction sites”, “cranes” and “construction projects”. Fig. 7(c) shows that a variety of solution methods has been used to address the problems related to SCM (e.g. “inventory control”, “scheduling” and “information management”). For example, its link strengths with “optimization”, “genetic algorithm”, and “game theory” are 4, 3, and 6, respectively. Also, “supply chain management” is connected to “radio frequency identification (RFID)”, “simulation”, and “building information modeling” with links strengths of 5, 5 and 3, respectively. However, the links between “supply chain management” and other keywords, such as “sustainability” and “risk management”, are weak. This reveals some research gaps. Fig. 7(d) shows that “manufacturing” is linked with the above-mentioned solution methods but with different link strengths. For instance, its link strengths with “optimization”, “genetic algorithm”, “simulation”, and “discrete event simulation” are 10, 5, 4, and 4, respectively. However, its link strengths with “life cycle assessment (LCA)”, “building information modeling”, and “artificial intelligence” are 4, 4 and 2, respectively. This indicates that optimization and simulation are the dominant methods used to solve production problems. However, Fig. 7(d) shows no links between “manufacturing” and “radio frequency identification (RFID)”, “risk management”, and “energy utilization”, highlighting some research gaps related to the production stage of the off-site construction. Fig. 7(e) shows that “architectural design” is connected to “manufacturing” and “construction sites” and “supply chain management” with link strengths of 4, 3, and 2, respectively. These results indicate that the limitations of the other SC stages need to be considered in the early stage of design. However, the weak link strengths indicate a dearth in the number of design studies that consider SC limitations. The network of “architectural design” reveals a number of its research problems represented by some keywords such as “decision making” (link strength = 4), “interoperability” (3), “automation” (3), and “information management” (3). Besides, the network shows some of the solution approaches used to solve these problems, such as “building information modeling” (link strength = 23), “decision support systems” (6), and “artificial intelligence” (4). These results signify the dominance of BIM in the design stage and highlight the need for more structural design studies which consider the constraints of the other SC stages. Finally, Fig. 7(f) shows some problems related to “logistics”, such as “inventory control” and “productivity”. These problems have been addressed with “optimization” and “building information modeling”. Again, Fig. 7(e) uncovers some research gaps related to the logistics stage of OSC-SCM. For example, the network does not show links between “logistics” and other potential research areas, such as “sustainability”, “risk management”, “lean production”, “internet of things”, and “artificial intelligence”.

Fig. 7

3.5.2 Citation burst analysis of keywords

Citation burst analysis shows the keywords that received surges in citations over a particular period (Chen, 2014). Therefore, it could be used to highlight the hot research topics over time. Fig. 8 shows the top 30 keywords with the strongest citation bursts sorted by the beginning year of the burst. Fig. 8 is generated by CiteSpace 5.7.R1. In Fig. 8, the red line associated with each keyword represents the time length of its citation burst. This is superimposed on the entire time range (cyan line) of the included studies (i.e., from 1985 to 2021). The burst strength of each keyword, a reflection of the number of citations received by a keyword during a particular period, was indicated in Fig. 8.

Fig. 8 shows that “genetic algorithm” (burst strength, 4.84; 2001-2010), “performance” (4.15; 2019-2020), “prefabrication” (3.70; 2019-2020) and “life cycle assessment” (3.27; 2019-2020) achieve the highest burst strength. This highlights the importance of these research topics in OSC-SCM. Regarding the length of citation bursts, Fig. 8 shows that “production planning” (burst strength, 2.38; 1994-2006), “scheduling” (2.43; 1994-2005), “heuristic algorithm” (2.09; 2001-2011) and “genetic algorithm” (4.84; 2001-2010) have received significant research attention for a relatively long period between 10 and 13 years. Moreover, Fig. 8 reveals some of the hot topics related to OSC-SCM in recent years, including “prefabricated component”, “greenhouse gas emission”, and “life cycle assessment”. Others include “prefabrication”, “performance”, “technology”, “internet”, “things”, “prefabricated construction”, “logistics”, “BIM”, and “resource”. These results indicate that researchers have significantly contributed to solving production planning and scheduling problems using approximate optimization approaches (e.g., heuristics and genetic algorithm (GA)). This finding concurs with the results of a review paper on the precast SCM (Wang et al., 2019). Besides, the keywords burst analysis highlights some hot topics for future research attention. These include assessment of the environmental impact using LCA and logistics management in OSC-SC using BIM and IoT technologies. These findings match the results of the co-occurrence network of keywords mentioned in point 3 in section 3.5.1.

Fig. 8

4. RESULTS AND DISCUSSION OF SYSTEMATIC REVIEW FOR OSC-SCM

The scientometric review provides only a high-level understanding and clustering of quantitative models on OSC-SCM. This, however, cannot help in identifying specific research gaps in the modelling of OSC-SC. Therefore, a systematic review is conducted on the same 309 studies used in the scientometric review to provide an in-depth understanding of the OSC-SC models. These studies are classified based on a three-dimensional classification. These are the OSC type, SC stage, and solution method. Each dimension consists of several subcategories. For instance, four types of OSC are identified. The first three types are used in building projects. They are classified based on the prefabrication level to construction-based PCs, panelized construction, and MiC. This classification matches the OSC classification adopted in the studies by Ayinla et al. (2019) and Innella et al. (2019). The fourth type is related to the OSC applied in infrastructure projects, such as bridges, tunnels, etc. The second dimension (SC stage) consists of five categories: design, production, logistics, on-site construction, and integrated SC stages. Finally, eight solution methods are frequently employed to address the different problems at each stage. These include optimization, simulation, LCA, BIM, PTS, AI, game theory, and hybrid methods. In the next sections, each OSC type, different problems at each SC stage, and solution methods applied are identified. In these sections, recent and highly cited articles are discussed for each problem type. Besides, the research gaps related to each SC stage of different OSC types are highlighted.

4.1 Construction-based PCs

This section explains the quantitative models developed in each stage of the SC of PCs. PCs include beams, columns, slabs, stairs, etc., produced off-site from different materials, such as reinforced concrete, steel, timber, etc. This OSC type has the least degree of prefabrication level; as still, many construction activities have to be conducted on-site.

4.1.1 Design stage

Before commencement of production operations, detailed designs of PCs have to be prepared and approved. This section discusses the different decisions made at the design stage and how the researchers have addressed these decision problems. Only ten out of 141 studies on the construction-based PCs are related to this stage. Table 4 summarizes these design problems, which include contract management, design for economic supply chain, design for lean construction, structural design, design for waste reduction and design information exchange. For contract management, Dawood (1996) has proposed a decision support system (DSS) to help managers make bidding decisions and estimate the optimum mark-up. This proposed system applied expert systems and information technology to learn from historical data and the experience of managers. Shi et al. (2018) have developed a game theory model to design a win-win incentive mechanism for the owners of mega projects to motivate the suppliers of PCs with the objective of increasing their quality, productivity and sustainability while maximizing the owner’s profit. Both of these studies discuss decisions that belong to the pre-contract phase without considering contract management during the construction and operating phases.

Table 4

Other researchers have proposed design approaches to achieve lean and sustainable objectives. For instance, Khalili and Chua (2013) have proposed a BIM-based optimization framework to find the optimum configurations/compounds of PCs that minimizes production, transportation and installation costs. The proposed framework could reduce the number of elemental PCs which are conventionally used while considering the manufacturability and constructability of the proposed configurations. Later, Gbadamosi et al. (2019) have proposed a BIM-based analytic hierarchy process (AHP) approach to help designers select the most suitable prefabricated elements and their materials. The selection is based on multiple criteria covering constructability, productivity and waste reduction factors. For structural design, optimization has been applied to automate the structural design of prefabricated buildings to minimize construction costs while satisfying the structural constraints. For instance, Chen et al. (2020) have used GA to automate the structural design process of post-tensioned precast concrete frames. Also, Navarro-Rubio et al. (2020) have applied a hybrid approach to finding the optimum structural design of precast connections using artificial neural network (ANN). The ANN was trained by using data obtained from a finite element (FE) model. Recently, due to the limitations of following the traditional mindset in designing floor plans of prefabricated housing projects, Cui et al. (2020) have developed multiple BIM libraries to find better floor plan designs while considering the standardization of PCs. Studying the effect of decisions made at the design stage on the generated construction wastes is another research problem. Baldwin et al. (2009) have applied the design structure matrix (DSM) to study the dependencies between the decisions of architectural, structural, construction, and building services design teams and evaluate their impact on the construction wastes produced on-site. The study suggests applying information models to engage other design teams with the architectural team as early as possible to avoid rework and hence reduce construction wastes. Finally, Rezaei Rad et al. (2021) contributed to the design data exchange problem between architectural and structural designers. The study proposes an algorithmic framework to automate the structural analysis of a timber plate structure using its 3D CAD geometry model as an input. Despite that these studies have covered a wide variety of design problems, little work has considered sustainability factors, especially environmental and social factors, in both the architectural and structural designs. Also, more studies are needed to estimate wastes associated with different design options.

4.1.2 Production stage

Upon receiving orders from the contractor, the production of PCs commences in a number of sequential operations. Fifty-two out of 141 studies on prefabricated construction have addressed different problems related to the production of PCs. These include production scheduling, resource allocation, integrated production scheduling and resource planning, lean production, green production, production layout, production control, and others, as shown in Table 5. This table represents a two-dimensional matrix based on problem types and solution methods. Each element of this matrix describes the number of studies that address a specific problem using a particular solution method. A colour map is used to better visualize the matrix. The high values are marked in green colour in this map; low values get yellowish-green colour, and zero value is assigned red colour.

Table 5

Fourteen out of the 52 studies on the production of PCs have focused on production scheduling problem. For instance, Ko and Wang (2010) have solved the flow shop-sequencing problem (FSSP) using a multi-objective GA while considering the buffer sizes between production stations. Three out of the 52 studies have investigated resource allocation problem. For example, Al-Bazi and Dawood (2010) have developed a GAs-based simulation approach to efficiently allocate crews of workers to manufacturing operations.

Twelve out of the 52 studies have integrated the resource allocation problem with the FSSP. Wang et al. (2018a) have presented a two-level optimization approach while considering the effect of workers' competence and their learning rate on production times. The proposed model has been solved using a GA-based approach, which achieved around 74% cost savings. Other studies have considered the stochastic nature of the problem parameters, e.g. stochastic arrival times of orders, uncertain due dates, resource shortage, and machine breakdown. For example, Ma et al. (2018) have proposed a production rescheduling approach to deal with any unpredicted event solved by GA. Their approach is based on response strategies, e.g. outsourcing orders, increasing working hours, and detecting over-estimated processing times. Recently, Jiang et al. (2020) have also considered the stochastic arrivals of multiple orders. They have proposed an optimization model solved by GA, in which three order acceptance strategies were considered. Another research has addressed the application of IoT technologies. Wang et al. (2018d) have proposed a multi-agent production planning system based on RFID. RFID technology monitored and collected real-time information during production operations. Then, production schedules and resource allocation were generated by using GA.

Eight out of the 52 studies focused on the green production problem. These studies addressed the issues of carbon emissions and energy consumption. For instance, Tao et al. (2018) have proposed an IoT-based platform that utilized RFID technology, a database, and laser sensors to collect and monitor real-time emissions information. The proposed platform resulted in a reduction of carbon emission. Recently, Wimala et al. (2019) have presented an artificial neural network-based approach for forecasting carbon emissions. They have validated their model using data from 107 precast concrete plants in Japan.

Only three out of the 52 studies have applied lean manufacturing techniques to prefabricated production. For instance, Li et al. (2018) have developed a lean production system based on constant work-in-process and a simulation model. The results showed that the developed system saved 25.4% of labour cost. Other studies have focused on production quality control and production layout. Kim et al. (2016) have considered quality assurance by developing an inspection technique that integrated laser scanning technologies and BIM. Regarding the production layout problem, Chen et al. (2016) have developed a reengineering-based approach to redesign the layout configuration of precast production. This achieved an overall 23.8% savings in production time.

Besides the problems mentioned above, other problems have been addressed. For example, Dawood (1994) has developed an integrated production management system, through a rules-based heuristic, for production scheduling and forecasting of demand and stock. Also, Hong et al. (2014) have argued that in-situ production of PCs could reduce production and transportation costs by 10% and 7 – 10%, respectively, compared with in-plant production. Later, Feng et al. (2017), through a game theory-based approach, have studied the cooperation and competition among prefabricators. The proposed incentive mechanism motivated partners to collaborate, and hence the quality of the product was further improved. Recently, Wagner et al. (2020) have proposed a largescale and movable robotic platform to produce prefabricated timber components for complex geometry structures. The platform's performance has been demonstrated in terms of quality, productivity, and sustainability.

Some research gaps have been found in the existing literature as follows:

1. Although several scholars proposed different FSSP approaches, these approaches were rarely compared with each other or other exact methods. Such comparisons are essential to determine the most superior approaches. Also, GA is the dominant solution method in the literature. Future research direction may focus on other optimization algorithms, such as swarm intelligence meta-heuristics, local search methods, and exact methods.
2. Future research may address larger problem datasets to evaluate the computational efficiency of the proposed approaches in practical problems. Additionally, benchmark instances of the FSSP are still lacking.
3. Simulation models were mostly used to handle the uncertainty in production operations. Still, stochastic optimization approaches were not utilized to find more reliable production schedules (Yusuf et al., 2019a). Besides, disturbance events and schedule recovery formed significant issues, though they were rarely studied. Future work may address different disturbance events in rescheduling approaches based on a rolling horizon strategy.
4. The state-of-the-art in the manufacturing and logistics industries involved collaborative and integrated planning of SC activities. Yet, this is rarely applied in the production planning of PCs. Future work may develop information sharing and collaborative planning approaches to enable collaboration among prefabricators.
5. There is a clear need for more research studies that consider carbon emission and energy consumption in a multi-objective approach with time and cost objectives. The tradeoffs among service quality (e.g., time and cost) and environmental impact (e.g., GHG emissions) have not been handled.

4.1.3 Logistics stage

After producing the PCs, these components are transported either to a consolidation centre or directly to the construction site according to the logistics plan. Eleven out of 141studies have addressed multiple logistics problems in prefabricated construction. These problems have been solved using a variety of solution methods, as shown in Table 6. Five types of logistics problems are identified. These problems are inventory management, procurement management, route planning, lean logistics, and other problems. On the focus of inventory management, Jaśkowski et al. (2018) have proposed a mixed-integer linear programming model to find the optimum economic order quantity that minimized the total inventory management costs. In procurement management, He et al. (2018) have proposed an e-commerce platform based on BIM to support the procurement process of PCs. With the wider adoption of PCs, route planning is needed to deliver the required PCs to multiple construction sites on time. Recently, Li et al. (2020) have mathematically modelled the dispatching problem of PCs as a vehicle routing problem (VRP) with time window solved by an approximate optimization method, namely, the improved artificial bee colony. The application of lean construction techniques to logistics management could minimize various wastes. Therefore, Bortolini et al. (2019) have proposed a 4D-BIM based approach to evaluate the merits of applying lean to the logistics management of PCs in terms of the project's duration, costs, and safety. Other researchers have addressed different problems. For instance, Fang and Ng (2011) have applied the activity-based costing (ABC) approach to estimate the cost of logistics and understand its activities. ABC is an accounting method used rather than traditional costing approaches to assign indirect costs to overhead activities and hence increase the accuracy of cost estimation and pricing. Ko (2013) have demonstrated, through a DES model, the cost-effectiveness of a cooperative transhipment strategy between multiple prefabricators to share raw materials between them. Later, Xu et al. (2019) have proposed an information management platform based on IoT technologies and cloud computing to help transportation companies manage their fleets. Recently, Yi et al. (2020) have developed a heuristic approach to find a near-optimum ship loading/staking plan of PCs in case of sea transportation. The objective is to minimize the number of shipping trips without exceeding the ship capacity limit.

Table 6

The research gaps related to the logistics management of PCs are provided as follows:

1- The previous studies ignored uncertainties related to demand variability, weather, traffic condition, equipment breakdown, absenteeism, and activities duration.
2- Only Li et al. (2020) have considered the energy consumption of moving trucks when solving the route planning problem. Therefore, more sustainability indicators should be considered.

3- The literature still lacks sustainable collaborative strategies between transportation companies when serving multiple construction sites simultaneously (Stefansson, 2006).

4.1.4 On-site construction stage

After the truck arrives at the construction site, the truck is unloaded. Then, each component is lifted to its destination in the building and connected to the other structural components (Yusuf et al., 2019b). This is the last stage of the SC of PCs. Twenty-three out of 141 studies on PCs have addressed various problems at this stage. Table 7 shows the problems associated with this stage and the research methods used to solve them. These problems are crane operation and planning (COP), construction risk management, project scheduling and resource planning, productivity assessment, green construction, and other problems. Six out of the 23 studies on the on-site stage are related to COP. For instance, Lien and Cheng (2014) have provided a mathematical optimization model to find the near-optimum locations of tower cranes and supply points using a hybrid meta-heuristics algorithm called particle-bee algorithm. Another topic related to crane operations is lift path planning. Li et al. (2020) have proposed a BIM-based approach to identify and prioritize potential obstacles and help in dynamic re-planning of the lift path by using the A* algorithm. Interested readers are invited to consult an in-depth review of crane layout problems conducted by Wang et al. (2021). Regarding risk management, Li et al. (2018a) have developed a multi-method simulation approach consisting of DES and system dynamics (SD) that evaluated the performance of assembly schedule under different risk scenarios. Also, Liu et al. (2018) have introduced a cloud model to assess the safety performance in construction sites by using AHP and entropy weight method. As for the project scheduling and resource planning problem, Wang et al. (2018) have proposed a mathematical optimization model to find the near-optimum assembly sequence of PCs that minimized the assembly time and cost. An improved GA solved the model, and the solution was visualized through a BIM model.

Table 7

Other researchers showed interest in productivity assessment. For example, Cho et al. (2017) have used DES to evaluate the benefits of using half-precast concrete slabs in terms of productivity and cost. Few researchers assessed the environmental impact of construction activities. Recently, Liu et al. (2020)

have proposed a cyber-physical system to monitor and visualize greenhouse gas (GHGs) emissions in real-time. The system collected information from construction equipment (e.g., cranes and construction elevators) using sensors. GHGs were evaluated by a quantitative model. Besides these problems, Wang et al. (2018) have proposed a 4D-BIM model to detect potential workspace conflict between workers during the assembly process. Similarly, Ji et al. (2019) have exploited a 4D-BIM model to estimate the costs of construction by considering the utilization of resources, the progress of the project, and incentive policies. Recently, Tang et al. (2020) have addressed the quality inspection problem of grout sleeve connections by developing a convolutional neural network (CNN)-based approach to detect defective joints.

Some research gaps related to the on-site construction stage are summarized in the following points:

1- More sustainability factors (i.e., economic, environmental, and social) are suggested to be considered in project scheduling and resource planning.
2- The effect of applying lean construction techniques on project key performance indicators (KPIs) (e.g., productivity, project's duration, cost, safety, etc.) has not been evaluated.
3- Previous researchers considered lifting activities in isolation from the other activities of a project. Considering these two types of activities may enrich the proposed planning.
4- Previous studies on risk management focused only on risk identification, risk prioritization, and risk assessment. However, risk response planning was not considered. A proactive risk response approach that predicts the potential disruptions and proposes the optimum risk response actions is required.

4.1.5 Integrated supply chain stages

The previous stages (i.e., production, logistics, and on-site installation) of the SC of PCs are interlinked. Therefore, many researchers have addressed a variety of problems associated with multiple SC stages. Forty-five out of 141studies have handled these types of problems. Table 8 shows the problems related to the SC of PCs and the solution methods used to address them. These problems are SC performance, collaborative supply chain, SC information management, tracking, SC risk management, green SC, sustainable SC, and others.

Table 8

Nine of the 45 studies on the prefabricated SC focus on SC performance. For example, Wang et al. (2017) have demonstrated, through a DES model, the efficiency of using RFID in reducing the operational costs and the lead time of the prefabricated supply chain. Also, Wang et al. (2018) have proposed a two-hierarchy simulation optimization model to develop the near-optimum production sequence of PCs by using GA. Then, they studied, through a DES model, the impact of the obtained production sequence on the performance of the logistics stages without considering the on-site installation stage. Recently, Liu et al. (2020) have proposed a multi-objective integer linear programming model to obtain the optimum storage plan of PCs. The model minimized relocation times and outbound and inbound transportation costs. In the collaborative SC problem, a win-win situation should be reached for multiple stakeholders. Seven out of the 45 studies have addressed this problem. For instance, Zhai et al. (2017) have proposed a coordination scheme to reach a win-win coordination scheme between the prefabricator and the contractor. Similarly, Zhai et al. (2018) have developed a coordination mechanism to reach a balance between the transporter and the contractor. Most studies on this problem type used game theory, as shown in Table 8. Lately, Chen et al. (2020) have proposed static and dynamic, collaborative scheduling mechanisms. The static one aims at finding the near-optimum time and resource schedules to minimize the total production and construction costs, while the dynamic one seeks to minimize the total costs incurred due to rescheduling in case of delays caused by supply chain disturbances. This developed optimization problem was solved by the simulated annealing algorithm.

Six out of the 45 studies have focused on information management in prefabricated SC. Chen et al. (2018) have proposed a physical internet-based BIM system to facilitate information collection, communication, and visualization through the prefabricated SC stages. Recently, Wang et al. (2020) have demonstrated the benefits of applying blockchain technology to the prefabricated SC in terms of its costs and lead time. Only three studies reported on the tracking of PCs across the SC stages. Ma et al. (2019) have developed an RFID-based BIM approach that connected two databases to visualize the state of information on PCs and tackle the problems of slow data exchange and update. Similarly, only three papers were found on the risk management of prefabricated SC. For instance, Wang et al. (2018b) have developed a DES model to evaluate the impact of multiple disturbances of the prefabricated SC on its costs. The results indicated that machine breakdown at the prefabricated plant was the most critical disturbance.

Of these 45 studies, eight have evaluated the environmental impact of the different stages of prefabricated SC. Mao et al. (2013) have proposed a quantitative model based on a process-based and micro-bottom-up method to estimate greenhouse gas emissions. Later, Casanovas-Rubio and Ramos (2017) have proposed a decision-making tool based on the multi-attribute utility theory to help in selecting the best construction method from the environmental perspective through an LCA. Recently, Ding et al. (2020) have developed a carbon emission measurement system for the prefabricated SC by using data extracted from BIM models. Only one study has considered more sustainability factors with the environmental dimension. Jeong et al. (2017) have estimated the cost, productivity, and CO_2 emissions associated with the SC of a type of prefabricated columns by using a DES model. They have estimated the CO_2 emissions produced during the production, transportation and construction stages. The emissions produced during the production stage have been estimated as the sum of the amount of each construction material multiplied by its emissions factor. The emissions of the transport vehicles were estimated based on the travelled distance, fuel type, and truck's capacity utilization. Finally, the emissions generated from the construction resources have been calculated as the sum of the total working time of each resource multiplied by its corresponding emissions factor. The model considered the difference between the emissions produced during the busy and idle times of each resource; these times have been obtained from the DES model.

Four additional studies have addressed other problem types. For instance, Babič et al. (2010) have integrated the benefits of BIM and enterprise resource planning (ERP) to monitor the on-site project progress and material flow management across the supply chain. Omar et al. (2018) have proposed a DSS to help in selecting manufacturers of prefabricated components. The DSS was based on fuzzy logic and the technique for order of preference by similarity to ideal solution (TOPSIS). TOPSIS is a multi-criteria decision-making approach used to identify the best alternative among a set of identified alternatives (Thakkar, 2021). Wang et al. (2018) have used the ABC method to build a computational model that estimated the total costs of the prefabricated SC. Finally, Hajdukiewicz et al. (2019) have proposed a platform for automated life cycle quality inspection of PCs to ensure their compliance with standards.

The research gaps related to the prefabricated SC are summarized as follows:

1- Decisions related to resource allocation, production, transportation, and inventory planning need to be integrated to reach a mutually beneficial SC for its stakeholders. This calls for integrating stochastic simulation modelling and optimization algorithms.
2- Most studies on the collaborative SC focused on the vertical collaboration between the different stages of the prefabricated SC. However, the horizontal collaboration between competitors at the same stage has not been addressed yet.
3- The three sustainability dimensions (i.e., economic, environmental, and social) need to be considered in the optimization models, aiming to enhance the SC performance.
4- Few studies have considered the interaction between multiple risks in prefabricated SC. Also, optimization of the risk response plan to mitigate potential risks while reducing the costs of risk response actions is missing.

4.2 Panelized Construction

Panelized construction includes two-dimensional building components that do not encompass a usable space, such as wall panels, facades, and floor and roof cassettes (Ayinla et al., 2019). Panelized construction has a higher prefabrication level than construction-based PCs. In this section, we discuss the main phases of panel SCM.

4.2.1 Design stage

Since panelized construction provides architectures with high design flexibility, especially for complex-geometry facades, detailed architectural and structural designs are required before starting the production operations. Eleven out of 51 studies on panelized construction have addressed its design problems. These studies can be clustered into four problem-based categories. These categories are architectural design, structural design, thermo-economic design, and lean design, as shown in Table 9.

Table 9

For architectural design, some studies have discussed the data interoperability issue between architectural and production BIM tools. For instance, Sacks et al. (2010) have compared designing precast facades using 2D computer-aided design (CAD) and BIM tools. The latter showed an increase in design productivity by about 60%. However, the study identifies some limitations in the exchange of geometric and other valuable data between architectural and production BIM tools, especially for complex-shaped facades, and calls for the need to a standardized BIM protocol to illustrate how precast facades can be modelled for seamless data interoperability. Other researchers tried to shrink the gap between architects and manufacturers by developing automated design models to reflect the architectural intent while satisfying the production constraints. Montali et al. (2019) have proposed a two-stage approach to integrate the manufacturing knowledge into the design process as early as possible. In the first stage, the authors have developed a knowledge-based tool to incorporate the knowledge of architects and manufacturers. Then, a heuristic optimization algorithm has been used to find the near-optimum design, which balances between the required architectural performance and the production constraints. Rather than using optimization approaches, other researchers resorted to multi-criteria decision making (MCDM) methods to compare different architectural designs. For instance, Frenette et al. (2010) have demonstrated the feasibility of using MCDM methods in identifying the most suitable design when considering multiple performance criteria.

Regarding the structural design in the panelized construction, researchers have applied optimization methods to find the optimum structural design that minimizes the material consumption and the production costs while satisfying different structural constraints (e.g., stress, buckling, deflection, etc.) (Mayencourt and Mueller, 2019). Said et al. (2017) have developed a multi-objective optimization model to find the near-optimum geometric and structural designs of wall panels that minimize the production cost while satisfying design flexibility. The model was solved using the non-dominated sorting genetic algorithm (NSGA).

For the thermo-economic design, the researchers have applied optimization methods to find the optimum insulation materials of panels and their thicknesses to reduce the energy costs of cooling and heating considering its life cycle cost (Ziapour et al., 2020). Other researchers have used optimization methods to find the optimum design that reduces production costs while satisfying both the structural and thermal constraints (Hodicky et al., 2015). Finally, Nath et al. (2015) have proposed a BIM-based approach to enhance the productivity of shop drawing output using value stream mapping (VSM). This lean technique (i.e., VSM) helped identify the non-value added activities (e.g., repetitive tasks, waiting times, etc.) in the shop drawing process. In general, lean techniques help identify non-value-added activities and different types of waste to eliminate them and continuously improve the system. Their main objective is responding to customer needs in less time and costs and higher quality (Martínez-Jurado and Moyano-Fuentes, 2014).

The previous studies have contributed significantly to the different design aspects of panelized construction. However, a handful of studies have addressed the data interoperability issues between architectural and structural BIM tools for off-site construction (Wu et al., 2021).

4.2.2 Production stage

Panel production could be considered the second stage in panel SCM, in which panels are initially prefabricated in an off-site production facility. For this stage, scholars focused on three main areas: production scheduling, resource allocation and quality inspection, as shown in Table 10.

Table 10

Regarding production scheduling, Leu and Hwang (2001) have proposed a model that determined a scheduling plan while considering limited resources, including crew and equipment. Their objective was to minimize the completion time of the production process by using GA. Despite considering some important aspects like resource limitation, the model failed to consider the stochastic feature of production times and the due date of the production process. In another study, Son et al. (2018) have discussed the production process of free form panels in the construction site. The authors proposed an algorithm to solve the production scheduling model to minimize the production cost. This model helped determine some useful information like the number of machines, production time, production areas, and others. The results showed a significant cost reduction while adopting the idea of in-site production. This model's pitfall is overlooking some risk factors like resource variability and machine breakdown.

Moreover, some studies on production scheduling focused on job sequencing. In this regard, Arashpour et al. (2016) have presented a model to efficiently define product sequencing to minimize the changeover time lost during switching between different product classes. The model was handled using a tabu search-based algorithm (an approximate optimization method). However, the model only considered a small size of product classes. Another job sequencing study was reported by Altaf et al. (2018). The authors have adopted RFID technology to obtain production data. Since the RFID output includes some noises, data analytics was implemented to remove these noises and produce accurate data. Next, these data were used as input to the simulation-based optimization model based on particle swarm optimization and simulated annealing to determine the production schedule in a reasonable time.

In the literature, the flow shop scheduling problem was also studied. Leu and Hwang (2002) have proposed a model that adopted the idea of a mixed production strategy. This means that the production line was utilized to produce multiple precast panels while considering resource limitations. Using GA, the optimization results showed that the mixed production strategy outperformed the separate production strategy in terms of the production makespan. Later, Arashpour et al. (2015) have developed a production tracking system using DES. This helped to observe some critical factors of the production process, like production output variability. The weakness of this model is that it ignored some factors like variability in the processing time and production resources.

Regarding the resource allocation problem, few studies were found. Leu and Hwang (2001) have developed a model (solved by GA) for providing a repetitive schedule while considering skilled labour and equipment availability constraints. The uniqueness of the model is that it considered resource sharing between project tasks. However, it overlooked some aspects, including the due date, activity durations uncertainty, and learning curve effects. Later, Arashpour et al. (2015b) have studied the concept of multi-skilled resources on production sites. They have demonstrated the effectiveness of this concept in improving the production process by using DES models. Finally, only one study has addressed the quality inspection problem in panel prefabrication facilities. Li and Kim (2021) have proposed a quality inspection mechanism based on terrestrial laser scanning without the need to merge point cloud data obtained from different scanning positions. The proposed mechanism depends on using flat mirrors to reflect the laser beam, which scans the invisible surfaces. The performance of the proposed mechanism has been demonstrated in terms of its accuracy and productivity.

The research gaps can be outlined as follows:

1. It is observed that the majority of production scheduling models are deterministic. Therefore, it is recommended to formulate production scheduling as a stochastic-based model following the formulation by Eltoukhy et al. (2018) while considering the uncertainty of production time and the number of workers.
2. Production scheduling and resource allocation problems belong to a single company with consistent objectives. However, both problems were solved separately, resulting in a sub-optimal problem. To avoid this, it is imperative to integrate production scheduling and resource allocation.
3. Most of the models were solved by adopting a single metaheuristic. This affected the searching capabilities of the algorithm and resulted in poor solution quality. Therefore, it is recommended to utilize hybrid metaheuristics to improve the searching mechanism of the algorithm.

4.2.3 Logistics stage

After producing the panels, they are transported to the construction sites, which is the third stage of the panel SCM. Indeed, this stage has been discussed in the literature under two main categories: just-in-time (JIT) delivery and transportation planning, as shown in Table 11.

Table 11

Regarding JIT delivery, Kong et al. (2018) have proposed a model that applies the concept of JIT to the SC by considering two main factors: the time of transportation and the time of on-site assembly. The proposed model aims at minimizing the total penalty costs by developing a polynomial-time algorithm. The pitfall of the model is that the transportation times are calculated based on limited traffic levels and homogenous vehicle types, which limits the applicability of the model in real practice. Further, Bamana et al. (2019) have presented a simulation model to evaluate the practical impact of JIT and lean principles on the completion time and labour utilization of a construction project. Although the proposed model was practically efficient, it is limited to wooden construction sites with medium sizes. Recently, Lyu et al. (2020) have developed a simulation model to propose the idea of zero-warehousing smart manufacturing, which implied removing any non-value-adding operations. The efficiency of the idea was shown in a case study in Hong Kong, where warehousing space was reduced. However, more case studies are required to improve the performance of the proposed concept.

On the transportation planning problem, Ahn et al. (2020) have focused on improving the estimation of transportation costs, which was previously calculated using a fixed cost approach. They have collected routing information using GIS techniques. The extracted data was used as input to support vector regression that predicted the transportation costs. Indeed, the collected data were more abstracted, as they only focused on loading and unloading data. Also, Yi et al. (2020) have proposed a mathematical model to determine the capacity of each truck used to transport the panels from the production site to the installation place. The model was developed to minimize the total cost, including the transportation cost and the inventory holding cost. The model was solved using a greedy algorithm (a heuristic optimization algorithm). However, the model only considered the weight of the product while overlooking the 3D volumetric features of the product. This could restrict the number of carried products, leading to inefficient truck utilization. Recently, Lee et al. (2021) have proposed a heuristic approach to automate the generation of near-optimum staking plans of exterior wall panels on A-frame trailers. The proposed approach helps in reducing the number of required trailer trips while minimizing the double-handling and ensuring the stability of transported panels.

This section reveals a limited number of logistics studies. Research gaps are as follows:

1. The literature lacks a concrete formulation for VRP and truck dispatching problem. Indeed, these formulations will help logistics companies to determine the truck capacity and the routes to be followed by each truck.
2. It will be more practical and accurate to consider different vehicle types with varying traffic levels while adopting the JIT delivery concept.

3. It is recommended to evaluate the impact of lean techniques, including JIT, on different project sizes.
4. It will be more interesting to consider more data collected via techniques like RFID, QR code, and computer vision techniques while predicting transportation costs.

4.2.4 On-site construction stage

After transporting the panel to the construction sites, they need to be assembled to finalize the process of building construction. In the literature, this stage can be divided into four main categories: crane planning, construction scheduling, construction site modelling and construction progress monitoring, as shown in Table 12.

Table 12

Manrique et al. (2007) have studied crane planning by adopting 3D modelling and animations to construct a complex construction building. In particular, the approach coupled a selection algorithm with 3D modelling and animation to select and allocate the cranes. This approach was aimed at minimizing the travelling times of the crane. Although the approach showed a reduction of about 14% in real practices, it was time-consuming.

Regarding construction scheduling, Shewchuk and Guo (2012) have discussed panel planning on the construction site. They have proposed a lean approach during panel planning so that stacking and sequencing of panels could be delivered to each layer of each stack. This approach aimed at minimizing the number of required stacks and reducing the handling distance of panels. To handle panel planning, the authors have proposed an algorithm that improved the results gained by design experts and commercial software. However, the algorithm overlooked some aspects, such as panel location and orientation in each layer. Later, Liu et al. (2015) have focused on activity scheduling on the construction site. The authors have applied BIM during designing the activity schedule of a construction project. Particle swarm optimization was adopted for designing the activity schedules. In a real case study, this idea showed sufficient performance in communicating with the project stakeholders besides building an optimized activity schedule. However, it had some drawbacks. Firstly, the activity duration and worker productivity were expert-based estimations. Secondly, the environmental aspects, like weather and site area limitation, were overlooked.

Based on construction site modelling, Dai and Lu (2013) have discussed how to use photogrammetry to make site modelling. This method includes taking photos of each object from two different camera stations, then making additional image processing for more understanding of the site elements. This facilitates making the geometric measurement and positioning of the site elements. Further, Li et al. (2015) have proposed a BIM-based training system. Its features included: 1) training the workers to improve their awareness of site hazards; 2) monitoring the movement of people and equipment on the construction site; and 3) providing real-time feedback for further improvement on site. However, it overlooked some hazards related to worker behaviours. Shewchuk et al. (2017) have modelled the workers' activities in a construction site and assessed the ergonomics of the physical processes. They have adopted DES to identify the duration, sequence, and classes of the worker activities to assess the system ergonomics. Despite the successful application of the proposed approach, it overlooked some physical aspects like body fatigue, and its application took a lot of time.

Besides the previously mentioned research problems, Wang et al. (2021) have proposed an automated framework for on-time construction progress monitoring of precast walls during the installation stage. The framework used deep learning approaches such as Mask R-CNN and DeepSORT to detect and track multiple walls from surveillance Video recordings. Then, the installation time and location information of detected walls are matched with their counterparts in a BIM model to allow for real-time progress monitoring.

After investigating the previous studies, research gaps are as follows:

1. Linking 3D modelling software with some kinematic software could be efficient in finding out the optimum crane locations.
2. Instead of using expert-based estimation to predict the activity durations, it is suggested to use data analytics techniques like cascaded neural network (Eltoukhy et al., 2019).
3. It is recommended to consider the hazards related to humans while modelling the on-site construction activities.

4.2.5 Integrated supply chain stages

In the previous sections, the stages of panel SC are discussed individually. However, some studies integrated these stages to avoid the plan conflicts that might arise from solving each stage individually. Indeed, a few integrated studies were reported in the literature, as shown in Table 13. For example, Kong et al. (2017) have presented a model that integrated the three stages of panel SC by considering constraints of production deadline and changeover costs. The model, whose objective was to maximize production efficiency, was solved by dynamic programming. Similarly, Li et al. (2017) have adopted RFID and BIM to make a platform to mitigate the delay. This system collected data like stakeholders, on-site information, and transportation data. However, the application of this platform may not be accepted globally. This is because the potential users of this system might not be knowledgeable enough about the technologies used in the developed system (e.g., RFID and BIM) (Li et al., 2017).

Table 13

Besides the previous studies, some studies focused on green SC. For instance, Dong et al. (2015) have conducted a cradle-to-site LCA to estimate the carbon emissions produced from using precast facades in residential buildings. They found that using these precast facades could reduce 6.5% of carbon emission compared with using traditional cast-in-situ construction. They found that this reduction in carbon emission is attributable to using steel formworks rather than timber ones. Later, Ji et al. (2018) have developed a four-dimension system boundary model to estimate GHG emissions generated from using the precast-in-situ construction method from cradle to site for residential buildings. They found that this method generated GHG emissions less than that produced from using the cast-in-situ construction method by 3.01%.

The previous studies centred on integrating SC operations and green SC. However, other studies focused on different aspects of SC, like analyzing SC costs. For example, Xue et al. (2018) have developed a factor analysis evaluation model to study the effect of latent factors behind the high capital cost of prefabricated construction. They found that increasing material and labour costs are significant factors. Also, the study recommended applying standardization and collaborative management to reduce capital costs. Kurpinska et al. (2019) demonstrated the economic feasibility of using a system of multi-layered panels made from lightweight concrete in terms of transportation and installation costs. Other studies incorporated BIM to SC. For instance, Alfieri et al. (2020) have proposed a six-stage framework to integrate BIM into prefabricated SC stages: design, production, and installation stages. The proposed framework has been developed for the Italian construction industry adapted from the British and the Singaporean well-established frameworks. The proposed framework has been applied to a case study and demonstrated its efficiency in organizing the data conveyed among SC stages.

Research gaps are as follows:

1. It is suggested to consider more sustainability factors like social factors in the domain of integrated SC.
2. There is a lack of coordination between the different stages of SC; therefore, conflicting goals are not well optimized.

4.3 MiC

MiC includes three-dimensional building modules that constitute a usable space, such as 3D frames, toilet, and kitchen pods (Ayinla et al., 2019). MiC has the highest prefabrication level, where on-site construction activities are minimal. This section illustrates the developed models at each stage of the MiC SC.

4.3.1 Design stage

The design decisions made at the early stage of MiC projects have a considerable impact on the performance of the other supply chain stages. Therefore, close coordination between design teams from different disciplines needs to be maintained (Hussein and Zayed, 2020b). This section summarizes the research problems and the proposed modelling methods in the design stage of MiC. Fourteen out of 98 studies on MiC have focused on the design stage. As shown in Table 14, these studies can be classified into four types based on design problems. For the architectural design, Wikberg et al. (2014) have proposed a BIM-based approach to incorporate both the architectural and the production views in the design stage through the configuration of architectural objects. The aim is to develop more flexible designs that meet customer's requirements while satisfying the production system limitations. Isaac et al. (2016) have proposed another approach to balancing customization and standardization through using non-repetitive modules with standardized interfaces. This approach would enable replacing a module (in case of any damages) easily without the need to replace many of its connected modules. Spatial design is another aspect of architectural design. They applied a clustering algorithm to the data obtained from a BIM model to cluster the modules with similar potential replacement rates while increasing their constructability. Sharafi et al. (2017) have proposed a DSM-based approach to assign the location of each module in the building. In this study, the spatial design of modules is modelled as a three-dimensional assignment problem. Moreover, the proposed approach suggested the best spatial design from the architectural (land usage and energy consumption), structural (connection system and structural eccentricity) and construction (transportation and installation costs) perspectives. Data interoperability between BIM tools of multi-disciplined design teams is one of the main barriers to the wide adoption of BIM in OSC (McGraw-Hill Construction, 2012). For instance, Ramaji and Memari (2018) highlighted the limitations of the information standards (e.g., model view definitions (MVD)) used for data exchange in traditional construction when using them in MiC. The study proposed MVD concepts to address these limitations for seamless interoperability between architectural and structural models.

Table 14

For structural design, researchers have used finite element methods to study the structural performance of different modular structures and their connections under various load conditions, including wind and seismic loads (Shan and Pan, 2020). Other studies have proposed new designs of inter-modular connections to withstand dynamic loads and studied their structural performance through FE models (Sendanayake et al., 2021). Besides using FE models solely, Gatheeshgar et al. (2020) have integrated particle swarm optimization (PSO) algorithm with a FE model in a hierarchical manner. The PSO finds the near-optimum cold-formed steel beams according to the Eurocode of steel structural design. Then, the flexural behaviour of the optimized design is analyzed in more details through the FE model. Since any errors in design and shop drawings during the production stage of MiC would lead to cost overrun and project delay, Alwisy et al. (2019) have developed an automated BIM-based approach that converts two-dimensional computer-aided design (CAD) drawings into a BIM model. This model provides the manufacturer with the required information for modules production, including their shop drawings and quantity take-offs. Recently, Gbadamosi et al. (2020) have introduced a big data repository of MiC design options to help clients selecting suitable design options (e.g., geometry and materials) and MiC suppliers. They supported this repository with an optimization approach to find the optimum design option in terms of multiple KPIs related to design, production, logistics, installation and operation stages. However, the proposed KPIs have been evaluated subjectively from expert opinions.

The authors expect that researchers will continue working on developing automated design models that consider the limitations of the production stage. Also, decision support systems (DSS) are required to compare potential designs and evaluate their performances from multiple design perspectives (e.g., architectural, structural and operational). Moreover, the capacity of the other supply chain stages (i.e., production, transportation and installation) needs to be considered in the proposed DSSs.

4.3.2 Production stage

After the architectural and structural designs, the production stage of the MiC SC commences in an off-site facility. Twenty-two out of 98 papers on MiC focused on this stage. Table 15 shows that these 22 papers focused on eight problems. These comprised resource planning, production scheduling, facility layout, integrated problems, ergonomic analysis, lean production, quality inspection, and other problems. For resource planning, Arashpour et al. (2018) have proposed a framework to identify optimal process integration and cross-training architecture of multi-skilled resources using a hybrid method of fuzzy-TOPSIS. Similarly, Nasirian et al. (2019) have developed a mathematical optimization model to solve the resource allocation problem with considering the merits of multi-skilled resources. However, Nam et al. (2019) have developed a DES model of production processes to help in resource levelling.

For the production scheduling problem, Hammad et al. (2020) have proposed a mixed-integer non-linear programming model to find the optimum production schedule to minimize the penalties associated with early and late deliveries. Chen et al. (2019) have proposed a hybrid simulation-based optimization model to solve the facility layout problem, which uses automated guided vehicles. Other researchers have integrated the problems mentioned above. For instance, Taghaddos et al. (2014) have addressed this integrated problem using a hybrid approach of DES and an auction protocol. Also, Sabharwal et al. (2009) have studied the impact of facility layout decisions on the production process using a DES model.

Regarding the ergonomic analysis problem, Golabchi et al. (2016) have proposed a fuzzy logic-based approach for on-site ergonomic assessment that was more accurate than the traditional evaluation methods. Other researchers have studied the applicability of some lean principles to minimize wastes. For example, Han et al. (2012) and Heravi and Firoozi (2017) have demonstrated the benefits of applying VSM as a lean technique through DES models. Regarding the quality inspection problem, Martinez et al. (2019) have developed a vision-based framework to compare real-time photos of MiC steel frames during the production process with its BIM to detect any deficiencies. Recently, Arashpour et al. (2020) have used laser scanning to collect real-time information on the produced modules and compared them with BIM models. Finally, other researchers have addressed other problems. For example, An et al. (2020) have proposed a BIM-based approach to evaluate the capability of a machine in MiC factories to produce a construction product. Rashid and Louis (2020) have demonstrated the applicability of using audio information generated from different production activities (e.g., nailing, hammering, drilling, etc.) to automate the identification and tracking of production activities in real-time. They have used support vector machine to classify the production activities.

Table 15

Research gaps in the production stage are as follows:

1- A handful of studies considered the disruptions that might impact the production process, such as low quality of raw materials, machine breakdown, absenteeism, and COVID-19 impacts. Therefore, most of the proposed approaches provided static production planning decisions. Also, the uncertainty of the production activities duration has not been considered.
2- The agile manufacturing principles need to be integrated into the production planning to respond quickly to demand variability due to on-site disruptions or design changes (Gunasekaran et al., 2019).

3- Few studies have considered the environmental impact when addressing MiC production problems.
4- Despite that, automated machines and Industry 4.0 technologies, such as robotics, Internet-of-things (IoT) and cyber-physical systems, have been acknowledged to revolutionize the manufacturing process of many industries (Bahrin et al., 2016), their application in MiC production is still limited.

4.3.3 Logistics stage

The logistics stage in the MiC SC includes transportation and storage operations conducted in between the MiC factory and the construction site. Only four out of 98 papers on MiC discussed these problems. Niu et al. (2017) have proposed an IoT system to improve real-time information management in MiC logistics. The developed system aimed to deliver the right information to the right person at the right time and in the right format. Liu et al. (2018) have provided overall guidance on some problems related to the transportation planning of MiC modules. These problems included selecting transportation modes, route planning, identifying a feasible road network to carry MiC modules, and estimation of transportation costs. Other researchers have studied the factors contributing to the damage of modules during transportation. For instance, Godbole et al. (2018) have modelled vertical accelerations transmitted to modules when transported on a rough road surface. Recently, Innella et al. (2020) have studied the effects of speed and road roughness on the structural behaviour of the transported modules.

Some research gaps related to the logistics of MiC are as follows:

1- With the wide adoption of MiC, multiple construction sites will ask for MiC modules simultaneously. Therefore, the transportation company needs to find the optimum route planning for its trucks while considering the delivery due date of modules for each construction site.
2- The optimum selection of transportation modes, especially for modules produced overseas, has not been addressed yet. To tackle this problem, there is a need to first identify the available transportation modes and then asses their economic and environmental impacts.

3- To hedge against any uncertainties along SC stages, a buffer of stored modules on-site or near the site (consolidation centre) needs to be kept. Finding the optimum buffer size, when to replenish it, and the optimum location of storage areas have not been studied yet.

4.3.4 On-site construction stage

Upon arrival, the trailer carrying the MiC module moves to the unloading area in the construction site (Moghadam et al., 2012). Then, workers unwrap the module and attach it to the crane hook. After the crane transports the module to its destination, it is connected to the adjacent modules through bolting and welding. This is the last stage in the MiC SC. Twenty-three out of 98 papers on MiC addressed problems related to this stage. Table 16 summarizes the problem types and their solution methods. The majority (65%) of these studies are related to COP because cranes are key resources in MiC projects. Regarding the lift path planning problem, Lei et al. (2013) have proposed an algorithm to check the validity of a potential lift path of mobile cranes. Later, Taghaddos et al. (2018) have proposed a more comprehensive approach to help plan multiple mobile crane operations, such as crane selection, crane location, and lift path planning. For more detailed information on COP in MiC, the reader can refer to (Hussein and Zayed, 2020a).

Table 16

Regarding the project scheduling and resource planning problems, Moghadam et al. (2012) have resorted to DES to capture the interactions between resources and the uncertainty in activities duration. The developed DES model was integrated with 3D visualization to estimate the project's cost and duration. However, the installation of mechanical, electrical, and plumbing (MEP) modules presents another challenge. The large MEP modules need to be divided into a number of smaller components to overcome space limitations and increase productivity and safety. Tserng et al. (2011) have addressed this problem using an optimization model with the aid of 3D visualization, while Samarasinghe et al. (2019) have used fuzzy logic and dependency structure matrix to identify the optimum number of sub-modules by using BIM models.

As for the application of lean principles, Goh and Goh (2019) have demonstrated the benefits of some lean principles, such as VSM, Total Quality Management (TQM), and Kanban system using a DES model. Recently, Zheng et al. (2020) have introduced an automated progress monitoring approach to detect modules during the installation process using Mask R-CNN. Synthetic images generated from virtual prototyping and transfer learning have been used to overcome some training issues such as the scarcity of real data and the long training time. Some researchers discussed other topics related to this stage. For instance, Martínez et al. (2013) have proposed a new system of robotized field factory and demonstrated its potential through a DES model. Recently, Li et al. (2018) have proposed an IoT-BIM platform for real-time information sharing between stakeholders of the construction stage.

The research limitations of the previous studies are summarized as follows:

1- Few studies considered crane operations and other on-site activities (i.e., truck arrival and manoeuvring, inspection process, and alignment) simultaneously. Therefore, more studies are required to provide more representative models of this interaction.
2- Most researchers addressed low to medium-rise MiC projects. High rise MiC projects in urban areas require considering additional factors, such as restricted working hours, limited storage space on-site, and parking space out of the site.
3- Many uncertainties at the construction site have not been considered in the developed models, such as weather conditions and truck arrival time variability.

4.3.5 Integrated supply chain stages

Of the 98 papers on MiC, 35 addressed the problems associated with multiple stages in the MiC SC simultaneously. These 33 papers handled seven types of problems using six solution methods, as shown in Table 17.

Table 17

In the SC performance problem, researchers investigated the impact of some decisions made at a particular stage on the performance of the whole SC. For example, Hsu et al. (2018) have developed a two-stage stochastic programming model that factored in on-site demand variability. The objective was to find the optimal production and logistics decisions that minimized the total costs of manufacturing, logistics, and construction. Lee and Hyun (2019) have integrated a simulation model of the MiC SC with GA. The model was implemented to find a near-optimum production sequence, number of transportation trucks, and on-site installation schedule of MiC modules to minimize the number of modules stacked on-site.

Considering the risk management problem in the MiC SC, dimensional and geometric variability of MiC modules were identified as critical risks. Therefore, many researchers proposed several approaches to identify and mitigate these risks. For instance, Shahtaheri et al. (2017) have proposed a framework to find the optimal design solution to minimize rework costs due to geometric variability risks considering the structural performance of the selected design solution. Later, Enshassi et al. (2019) have proposed a framework to identify tolerance and alignment risks through laser scanning and BIM models. Then, the Monte Carlo simulation was used to assess these risks. Finally, mitigation actions were equally proposed. Other researchers have addressed other types of risks. For example, Li et al. (2013) have developed a framework to identify and prioritize different risks in MiC SC by using fuzzy-AHP. Then, the framework assessed the impact of these risks on the project's costs and its duration by using a DES model. Recently, Hsu et al. (2019) have developed a robust optimization model to find the optimal production and logistics decisions that minimized total costs at different stages of the supply chain while considering the on-site demand variability.

Regarding the application of lean techniques, Li et al. (2018) have developed a simulation game to train students and practitioners on the benefits of integrating some lean principles with RFID and BIM technologies. Recently, Heravi et al. (2019) have used DES to assess the effect of different lean principles, such as JIT, VSM, and total productive maintenance (TPM), on total project's duration and costs. Other researchers, however, focused on the evaluation of the environmental impacts of the MiC SC through LCA analysis. Quale et al. (2012) have conducted a cradle-to-gate LCA study to assess the environmental impacts of MiC operations related to materials production, transportation, and installation. Tavares et al. (2019) expanded the contributions of Quale et al. (2012) by evaluating the embodied energy and GHGs of raw materials production, transportation of workers, and finishing operations on-site. However, the sustainability of SC requires considering its three pillars (i.e., economic, environmental, and social). Hammad et al. (2019) have developed an automated DSS to help in the decision of MiC adoption by comparing it with the traditional construction method based on the three sustainability dimensions.

Regarding information sharing between the stakeholders of MiC SC to enhance its performance, IoT technologies, such as RFID, GPS, sensors on-site, etc., were integrated with BIM models for real-time information sharing (Zhai et al., 2019). Finally, other researchers have addressed different types of problems. For example, Goulding et al. (2012) have developed a virtual reality model for the production and installation stages of the MiC SC for training purposes to enhance safety. Also, Mostafa and Chileshe (2018) have developed a DES model to evaluate the effects of client order behaviour on the project's time and cost.

The research gaps of the previous studies are as follows:

1- There are some challenges regarding the application of IoT in the MiC SC. These challenges are 1) interoperability of connected systems distributed among the SC stages; 2) authentication, traceability, transparency, and security of large volume of data obtained from IoT; and 3) unavailability of the internet in some stages, especially during transportation.
2- More sustainability factors, especially environmental and social factors, need to be considered when optimizing the SC performance.
3- The previous studies have focused mainly on risk identification and assessment procedures of specific risks, namely, geometric variability and site-demand variability risks. Therefore, there is a need for holistic risk management DSSs for MiC SC. These DSSs should have the ability to conduct other risk management procedures such as risk response and risk monitoring and control besides the risk identification and assessment. Moreover, they need to consider more SC risks and their interrelationships to provide informative risk management decisions in terms of the three sustainability factors (i.e., economic, environmental and social factors).
4- The majority of previous studies assumed deterministic values for the duration of different operations at SC stages and also for GHG emissions and energy consumption. This assumption impacted the reliability of the proposed models.

4.4 Construction of Civil Infrastructure

The OSC has been applied to infrastructure projects (e.g., bridges, tunnels, etc.) mainly to mitigate the impact of the traditional cast-in-situ construction method on traffic condition (Salimi et al., 2018). This section summarizes the different stages of the SCs of these infrastructure projects. Nineteen out of the 309 studies addressed problems in these SCs. Three out of these fifteen studies addressed problems related to tunnelling projects using precast lining segments, while the remaining studies were focused on bridge construction projects using precast or steel girders or precast deck panels.

Four studies have addressed some decisions made at the design stage. Two of them focused on the economic structural design of precast prestressed beams for road bridge projects (Martí et al., 2015). These studies have proposed hybrid metaheuristics to find the near-optimum structural design that minimizes the production, transportation, and installation costs while satisfying the geometric and structural constraints. Martí et al. (2013) have integrated simulated annealing and a neighbourhood search inspired from the GA, while Martí et al. (2015) have hybridized the memetic algorithm with the variable-depth neighbourhood search. Using the same hybrid metaheuristic, Penadés-Plà et al. (2018) have proposed a two-stage sequential approach to find the near-optimum structural design that minimizes both the cost and the environmental impact. This approach firstly applies the optimization to find the economic design and then evaluates its environmental impact through LCA. Recently, Cicconi et al. (2020) have proposed a multi-objective optimization approach using multi-objective genetic algorithm MOGA-II to find the near-optimum design of prefabricated steel towers used in oil and gas chimneys. The proposed approach provides the decision-maker with a near-optimum design that minimizes the weight and costs during the bidding and construction phases. Despite the contributions of the previous studies, other sustainability factors besides the economic ones need to be included in the design optimization process with considering the whole project life cycle.

Only three studies focused on the production stage. Regarding resource planning and management, Liu and Lu (2018) have proposed a mathematical model solved by a constraint programming approach to minimize the direct crew costs and material inventory costs. Later, this mathematical model was further developed to optimize the resource allocation problem for concurrent projects to minimize the project's duration and the fluctuation of utilizing resources (Liu and Lu, 2020). However, the previous studies assumed deterministic duration of production activities. Therefore, there is a need to consider the variability of activities duration to better reflect the production environment. Quality inspection of the produced components at prefabricated facilities is another production problem. Prefabricators need to ensure proper quality assurance and quality control (QA/QC) of the produced components to maintain their reputation. Any defects in these components detected at the construction site might lead to re-shipment or reproduction of components. Still, if defects are not detected, they might jeopardize the structure's stability (Li and Kim, 2021). However, manual inspection methods currently used in prefabricated facilities are time-consuming and prone-to-errors, especially for large components. Therefore, Wang et al. (2018) have proposed an automated approach for the dimensional quality inspection of prefabricated bridge deck panels. The poor dimensional quality of these panels impacts the structural integrity of their connections. The proposed approach creates an as-built BIM model using laser scanning data but without the need for a complete as-designed BIM model.

Only one study on the logistics problems of infrastructure projects was reported. The study proposed a fuzzy control system to increase the synchronization accuracy of hydraulic cylinders used to lift huge bridge girders in special transport trailers (Wang et al., 2019). Nevertheless, the literature still lacks studies on the route planning of such heavy and bulky components in urban areas. Also, these projects require careful inventory management to avoid stacking such huge components.

Six out of 19 studies addressed different problems at the construction site. Three of these studies applied simulation modelling to solve the site layout planning problems. For instance, Chan and Lu (2008) have proposed a DES model to evaluate the effectiveness of alternative material handling systems in precast bridge construction projects. Later, Scheffer et al. (2016) have integrated DES with continuous simulation to improve the site layout planning of tunnel construction. However, using simulation modelling alone cannot obtain the optimum site layout plan. Therefore, future studies can integrate optimization algorithms with simulation modelling to find the optimum site layout plan.

Other researchers used DES to estimate productivity and resource utilization (Hong and Hastak, 2007). Recently, some researchers applied laser scanning to detect the dimensional errors of arrived PCs. For example, Yoon et al. (2018) have extracted the locations of shear connectors of precast bridge deck slabs using clustering algorithms from scanned data. Then, they have determined the optimal placement of the deck slabs by using the Levenberg-Marquardt optimization method.

Five out of 19 studies considered multiple stages in the SC of the prefabricated infrastructure projects. Du et al. (2017) have proposed an information tracking system of precast tunnel segments based on RFID and agent-based simulation. However, Pan et al. (2008) have used the DES modelling to evaluate the performance of the whole SC in terms of some KPIs (e.g., project's duration and cost). Other researchers have integrated DES models with optimization algorithms to find the near-optimum number of different resource crews and other related decision variables (e.g., overtime policy, location of the precast yard, etc.) (Marzouk et al., 2009). Recently, Mawlana and Hammad (2019) have integrated such simulation-optimization models with parallel computing and variance reduction techniques to reduce the computation time.

Despite the previous studies' contribution, there is still room for further improvements as follows.

1- Environmental and social impacts have not been considered in previous studies. Therefore, future studies can address the problems mentioned above, considering sustainability factors.
2- There are many risks and disruptions along different stages of this supply chain. More studies are required on disruption management, including disruption identification, disruption assessment, and disruption control.
3- More studies are required to study how different lean construction techniques (e.g., JIT, 5S, last planner system, VSM, etc.) can improve the performance of the SC of infrastructure projects.
4- Since many studies applied simulation, modelling, and optimization to enhance the performance of the supply chain, new simulation-based optimization methods are needed to reduce the computational time. Such methods may include metamodeling by using surrogate models and ANN.
5- Laser scanning is important in assessing the quality of PCs. However, new technologies are required to tackle the sensitivity of the laser scanning method to weather conditions and

vibrations. These new technologies include Unmanned Aerial Vehicle (UAV)-based cameras and UAV (such as drones)-based Light Detection and Ranging (LiDAR).

4.5 Concise Classification of Modelling Studies on OSC-SCM

To summarize the previous discussion, Figs. 9 and 10 show a three-dimensional classification of the 309 modelling studies on OSC-SCM. Fig. 9 shows the number of studies associated with OSC types and SC stages, while Fig. 10 shows the number of studies on each SC stage and the adopted solution methods. Note that Fig. 10 shows only the most frequent solution methods. A colour map is used to better visualize these matrices. Besides, Figs. 9 and 10 provide a graph of the research trend over the years for each type of OSC, SC stage, and solution method. Each graph is supplemented with a third-degree polynomial trend line to show the accumulation of knowledge of each of these research areas. Therefore, these figures provide an overview of the mainstream research on the modelling of OSC-SC and hence can guide researchers in identifying research areas that need further studies.

Fig. 9

Fig. 10

Fig. 9 shows that the construction-based PCs has received the most attention from previous researchers, followed by MiC, panelized construction, and infrastructure. This matches the results of the keyword network mentioned in points 1 and 2 of section 3.5.1. Regarding the SC stages, previous researchers paid most attention to solving problems at the production stage. Next in priority are the problems at the on-site construction, design and logistics stages. This agrees with the findings of the keyword network mentioned in point 1 of section 3.5.1. However, researchers preferred to integrate problems in multiple stages rather than focus on single-stage problems. The highest number of studies are dedicated to addressing problems related to PCs production, as demonstrated in Fig. 7(b). However, the few numbers of studies on infrastructure projects and the logistics stage in all OSC types may motivate researchers to contribute more to these abandoned yet critical research areas. Likewise, this agrees with the potential hot research topics predicted by the citation burst analysis of keywords. The research trends of OSC types indicate that the fastest research growth belongs to construction-based PCs, panelized construction, and MiC. Conversely, research on civil infrastructure grows at a slower pace. Regarding the SC stages, research on the design, production, logistics, and integrated SC stages experience faster growth, while a constant growth rate is observed in the research trend of the installation stage. These trends indicate the inclination of researchers to continue working on problems related to the design, production, logistics, and integrated SC stages of the supply chains of PCs, panels, and MiC modules.

Fig. 10 shows that the most frequent solution methods used to solve problems of the different stages of the OSC-SCM are optimization, simulation, BIM, and LCA, respectively. In general, optimization algorithms, especially metaheuristics, have been used to find the optimum or near-optimum operational decisions among multiple alternatives in each SC stage. Some of these decisions are structural and thermo-economic design in the design stage, production scheduling and resource planning in the production stage, inventory management and routing planning in the logistics stage, and crane operation planning in the installation stage. Simulation approaches have been used to simulate complex systems and consider the uncertainty that originated from multiple disruptions at each SC stage, such as demand variability at the production stage, traffic congestions at the logistics stage, and severe weather conditions at the installation stage. BIM models have been used extensively in the design stage to improve communication among the multi-disciplined design teams and the other SC members. They have also been used in the installation stage to ensure that lifting plans are collision-free. LCA has been used to assess the environmental impact of alternative designs and compare between OSC types and traditional construction methods. However, researchers tended more to use multiple solution methods within the same study. As shown in Fig. 10, the most frequent solution methods used to solve problems at a particular SC stage are optimization for the production stage (34 studies), LCA for integrated SC stages (19 studies), and simulation for the production stage (13 studies). Similarly, this concurs with the findings of the keyword network mentioned in point 3 of section 3.5.1. Fig. 10 shows that optimization, AI, BIM, game theory, and hybrid methods have the fastest-growing research trend, while the research trends of using simulation and LCA are increasing at a constant rate. Both cooperative and non-cooperative game theory models have been used to study the situations in which the competition or cooperation among SC members affects their profits. Therefore, most studies that adopted game theory have considered multiple stages, as shown in Fig. 10. AI methods have been frequently used in decision-making problems characterized by uncertainty, such as supplier selection. On the contrary, the trend of using PTS as an individual solution method flatten. This shows that optimization, BIM, AI, game theory and method hybridization are most likely to continue to be the chosen solution methods for researchers.

Based on the systematic analysis conducted in section 4, the consideration of the three sustainability dimensions (i.e., economic, environmental, and social) in the modelling studies of OSC-SC has been summarized in Fig. 11. Fig. 11(a) shows the frequency of considering the three sustainability dimensions in each SC stage. The figure shows that the economic dimension is the most frequent sustainability dimension considered in SC stages, followed by the environmental and social dimensions. Also, Fig. 11(a) shows that the largest portion of studies on environmental sustainability is recorded at the integrated supply chain stages. This finding is attributable to the LCA studies, which considered the environmental impact of multiple-SC stages. Interestingly, social sustainability has been rarely considered in the design and logistics stages of OSC-SC. Consequently, this finding calls future researchers to contribute to the problems discussed in section 4 by considering more sustainability dimensions, especially the social one. From the perspective of OSC types, Fig. 11(b) indicates that again, the economic aspect is the most sustainability dimension addressed in previous studies, followed by the environmental and social aspects. The figure also shows that most studies on environmental sustainability have been conducted on construction-based PCs. This might be attributable to the fact that this construction method is the oldest among the other types (Abdelmageed and Zayed, 2020). Therefore, many case studies of real projects were available to conduct studies and analysis of the environmental impact of construction-based PCs. As for social sustainability, most of its studies have been focused on MiC due to the relatively new interest in ergonomics of workers inside MiC factories and the reduction of safety hazards and noise pollution during the installation of MiC modules. In summary, Fig. 12(a) shows that economic, environmental and social sustainability aspects have been considered in previous studies on OSC-SC by 72%, 24% and 4%, respectively. These findings concur with the findings of Rajeev et al. (2017), who conducted a review study on the sustainability in SCM for a wide variety of industries and again found that economic sustainability has been paid much attention than the environmental and social sustainability, as shown in Fig. 12(b). However, the gap between the percentages of studies that considered the environmental and social sustainability in OSC-SC and other industries could incentivize future researchers to contribute to OSC-SCM by considering environmental and social sustainability indicators when solving its managerial and operational problems mentioned in section 4.

Fig. 11

Fig. 12

5. FUTURE RESEARCH DIRECTIONS FOR SUSTAINABLE OSC-SC

Fig. 13 summarizes the future research opportunities in modelling the different stages of SC of PCs, panels, and MiC modules. These research opportunities are identified from the scientometric and systematic reviews of OSC-SCM conducted in the previous sections. As MiC is the most recent type of OSC and has the highest prefabrication level, its future research opportunities are discussed in the following points. These research opportunities are identified from the studies on SCs of MiC, PCs, and panels.

Fig. 13

1- The decisions made during the design stage of MiC have a considerable impact not only on the other SC stages but also on the other project phases. Besides, the design team might not be aware of all of these impacts, especially those related to other disciplines. Therefore, there is an urgent need to integrate the knowledge of multi-disciplined design teams and the other SC members (i.e., manufacturers, transporters, contractors and facility managers). This knowledge repository can be supported with decision support systems (DSSs) to evaluate potential design options in terms of manufacturability, transportability, constructability and maintainability. In the era of big data, cloud computing, BIM and AI, this knowledge repository is achievable. Besides, the developed DSSs need to assess the design options based on the three sustainability factors, namely, economic (reducing SC and operating costs), environmental (minimization of operational and embodied emissions, and water footprint) and social (design customization and less disturbance in case of module replacement for maintenance) factors. A handful of studies have considered social sustainability in MiC design.

2- For the production stage, firstly, the development of benchmark instances for the flow shop sequencing problem of MiC production is imperative to evaluate the performance of proposed metaheuristics. Secondly, dynamic and agile production planning models are required to respond to disturbances at the production stage (e.g., machine breakdown, late delivery of raw materials, worker absenteeism, etc.) in real-time. Thirdly, social (e.g., ergonomics, safety, etc.) and environmental (GHG emissions, energy consumption, etc.) factors, in addition to the economic aspect, should be considered when optimizing production scheduling and resource allocation. Besides, sustainable treatment of wastewater produced from production operations in MiC factories has been ignored in the literature. Nitrifying-enriched activated sludge (NAS) is a potential approach to achieve this objective (Sepehri and Sarrafzadeh, 2018; Sepehri and Sarrafzadeh, 2019; Sepehri et al., 2020). Finally, the feasibility of integrating automated machines (An et al., 2020) and industry 4.0 technologies (e.g., IoT, cyber-physical systems and robotics) (Cai et al., 2019) into MiC factories is worthy of being investigated.

3- For the logistics stage, optimization models for vehicle routing and truck dispatching problems are essential for the on-time delivery of MiC modules. These models should incorporate diverse vehicle types and different traffic levels while considering environmental and social impacts (e.g., emissions and traffic congestion, respectively). Next, a DSS that accounts for economic and environmental impacts is required to select the optimum transportation mode to convey modules produced overseas. Thirdly, location optimization of consolidation centres to hedge against late delivery is still lacking in the literature. Lastly, economic impacts (e.g., transportation costs, storage costs and late delivery penalties), environmental impacts (e.g., energy consumption, emissions, wastes) and social impacts (e.g., safety, traffic congestion, noise, accidents) of applying lean techniques, including JIT, in MiC logistics need to be quantified to study the feasibility of adopting these techniques.

4- For the on-site construction stage, simultaneous scheduling optimization of crane operations and other construction activities need to be considered. Thereafter, site layout planning models for high-rise MiC projects in dense urban areas should be developed. These models should estimate the sustainability impact of the proposed site layout plans in terms of their impact on the traffic flow and the surrounding environment.

5- For the integrated supply chain, blockchain may be integrated with IoT to enhance information sharing, traceability, and security among the MiC supply chain stakeholders. Secondly, very few studies have considered the impact on sustainability factors when optimizing the performance of the MiC supply chain under uncertainty. Thirdly, smart distribution management DSSs are required to monitor SC disruptions in real-time and respond intelligently to potential disruptions. Such systems will have the ability to predict potential disruptions by learning from historical disruption data. Optimization models embedded in these systems could be used to find the optimum SC designs and mitigation actions for potential disruptions.

6. CONCLUSIONS

Previous review studies on OSC either lack a detailed analysis of the modelling of its SC or are limited to specific OSC types such as construction-based precast components without considering the other types. Therefore, this research contributes by providing a comprehensive review of the trends and developments in the modelling of OSC-SC to identify the research gaps and highlight future research opportunities. Collectively, 309 relevant studies are critically analysed by combining scientometric and systematic review approaches. This method provides an in-depth review of the topic under study while minimizing subjective judgment and biased conclusions.

The scientometric analysis indicates that: 1) *Automation in Construction*, *Journal of Cleaner Production* and *Journal of Construction Engineering and Management* are the top most prolific and influential research outlets in the modelling of OSC-SC; 2) researchers with the highest contributions to this research field are Al-Hussein M. Hu H., Shen G.Q., and Xue F.; and 3) the topmost cited five articles are the studies by Monahan and Powell (2011), Ergen et al. (2007a), Mao et al. (2013), Garrido et al. (2008), and Jeong et al. (2009). Besides, the co-occurrence network and burst analysis of keywords are conducted to map the research areas and identify hot topics, respectively. The keywords network shows that: 1) researchers have focused more on the construction-based PCs than MiC; 2) modelling research on OSC-SCM is dedicated more to building projects than infrastructure projects; 3) in MiC, studies on the production stage are more than those on the on-site installation and design stages; and the number of studies on the logistics of MiC modules is the least; 4) in the construction-based PCs, the number of studies, which consider multiple SC stages, are higher than those on the design and logistics stages combined. However, there are plenty of studies that have addressed a variety of production problems of PCs; 5) optimization, simulation, LCA and BIM are the most frequent solution methods used to tackle different problems at each of the OSC-SC stages; and 6) some keywords, such as "logistics", "sustainability", "energy utilization", "risk management", "lean production", "resource", "internet of things", and "artificial intelligence", are rarely used. Therefore, future researchers can work in these abandoned, yet critical research areas. These findings have been confirmed by the citation burst analysis of keywords.

The systematic review is conducted by classifying the included studies based on OSC types, SC stages, solution methods and problem types. The OSC types are construction-based PCs, panelized construction, MiC, and civil infrastructure. The results indicate that most of the studies focus on construction-based PCs, followed by MiC, panelized construction, and civil infrastructure. Then, the studies of each OSC type are classified based on SC stages (i.e., design, production, logistics, on-site construction, and integrated SC stages). Similar to the scientometric review results, most of the studies focus on the production stage, followed by on-site construction, design and logistics stages. However, researchers tend more to consider multiple stages within the same study than modelling one stage. After that, the studies of each SC stage of individual OSC type are further classified based on problem types and solution methods. Hence, research gaps related to each SC stage of individual OSC type are identified. The problems at each SC stage have been frequently solved by optimization, simulation, LCA, BIM, PTS, AI, and game theory. However, researchers favour integrating multiple solution methods within the same study over using single solution methods. The in-depth analysis shows that the most frequent techniques used in each solution method are GA in optimization, DES in simulation, cradle-to-gate in

LCA, 3D BIM models in BIM dimensions, RFID in PTS, ANN and fuzzy logic in AI and Nash equilibrium and Stackelberg game in game theory.

Based on the findings of the scientometric and systematic reviews, it is found that economic, environmental and social sustainability aspects have been considered in previous studies on OSC-SC by 72%, 24% and 4%, respectively. Environmental sustainability has been addressed mainly in LCA studies to compare alternative construction methods, while very little attention has been paid to social sustainability indicators in OSC-SC stages. Since MiC has the highest prefabrication level and is relatively new, its future research directions are highlighted to encourage future researchers to consider more environmental and social sustainability factors when solving OSC-SC problems. For instance, in the design stage, there is a need to integrate the knowledge of design teams and supply chain members into one data repository to ensure the suitability of potential designs to all MiC stakeholders. Also, DSS is required to evaluate potential designs based on the three sustainability factors. Secondly, in the production stage of MiC, the SC would benefit from developing dynamic and agile production planning approaches to respond to disturbances in real-time with the aid of Industry 4.0 technologies. Thirdly, in the logistics stage, the development of DSS is required to select the optimum transportation mode in case of modules produced overseas considering its economic and environmental impacts. Fourthly, at MiC construction sites, a systematic risk management approach is required to identify, assess and respond to potential risks. Finally, to improve the performance of the whole MiC-SC, integration of IoT, operations research techniques and blockchain would help make optimum SC decisions in real-time and with minimal effects on the three sustainability factors. More details on the future research directions are explained in section 5.

Despite the contributions of this research, some limitations are highlighted. Firstly, the authors might have missed some related studies on the modelling of OSC-SC despite using a wide range of related keywords. However, the results of this study can adequately reflect the trend in the modelling of OSC-SC. Secondly, some scientometric analyses are not included here, such as the network of active institutions and countries, so as not to further lengthen the paper. Besides, the analysis of active researchers can reflect the active institutions and countries.

The information presented in this research is invaluable to both OSC-SC partners and researchers who are interested in OSC-SCM research. OSC-SC partners are provided with an identification of different problems related to each stage in the OSC-SC and how researchers have addressed these problems. This would foster more collaboration between OSC-SC partners to bring innovation and enhancement to the performance of SC. In particular, researchers will benefit from the research opportunities identified here to develop the existing body of knowledge on the modelling of OSC-SC.

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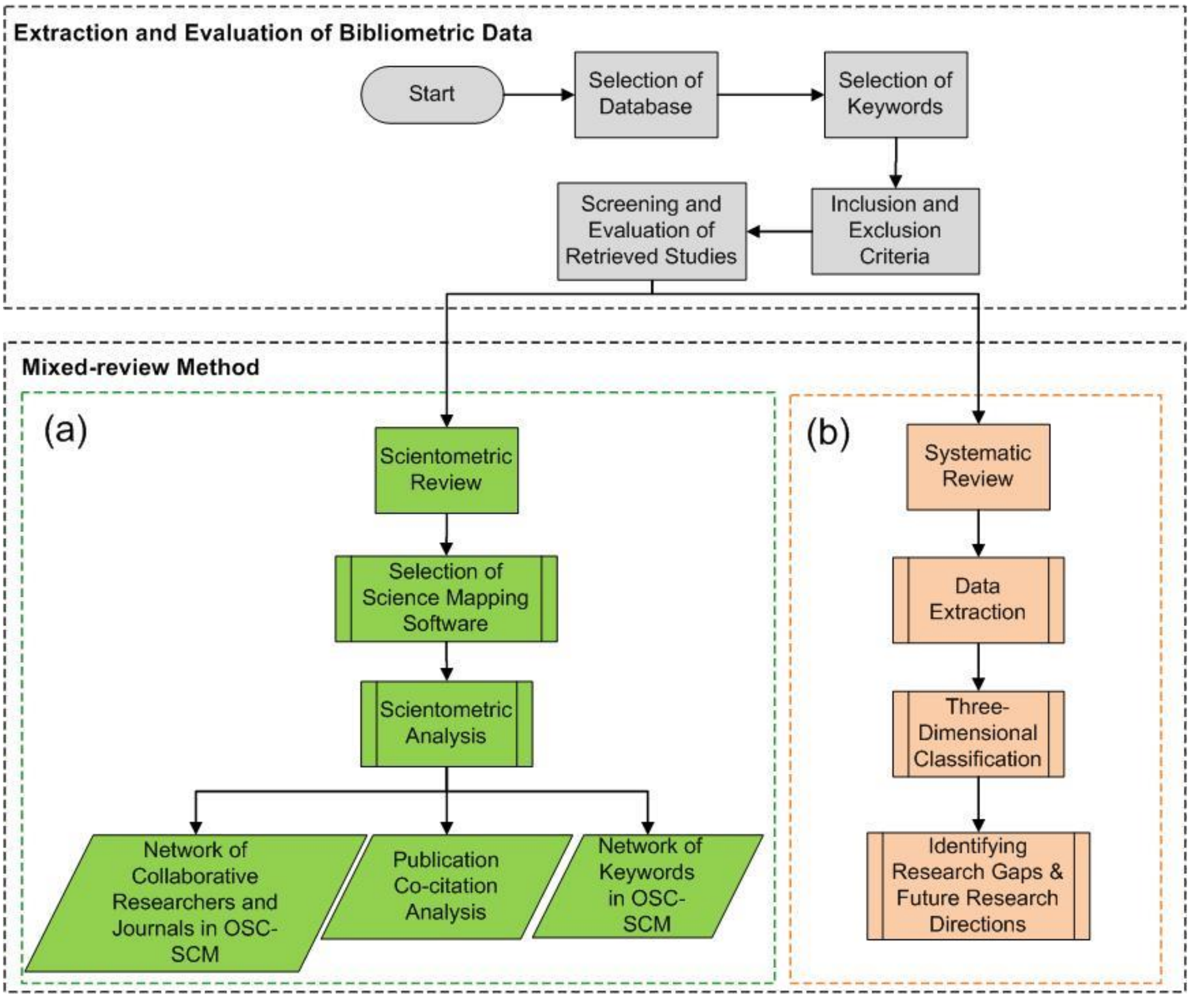


Fig. 1: Outline of the review methodology.

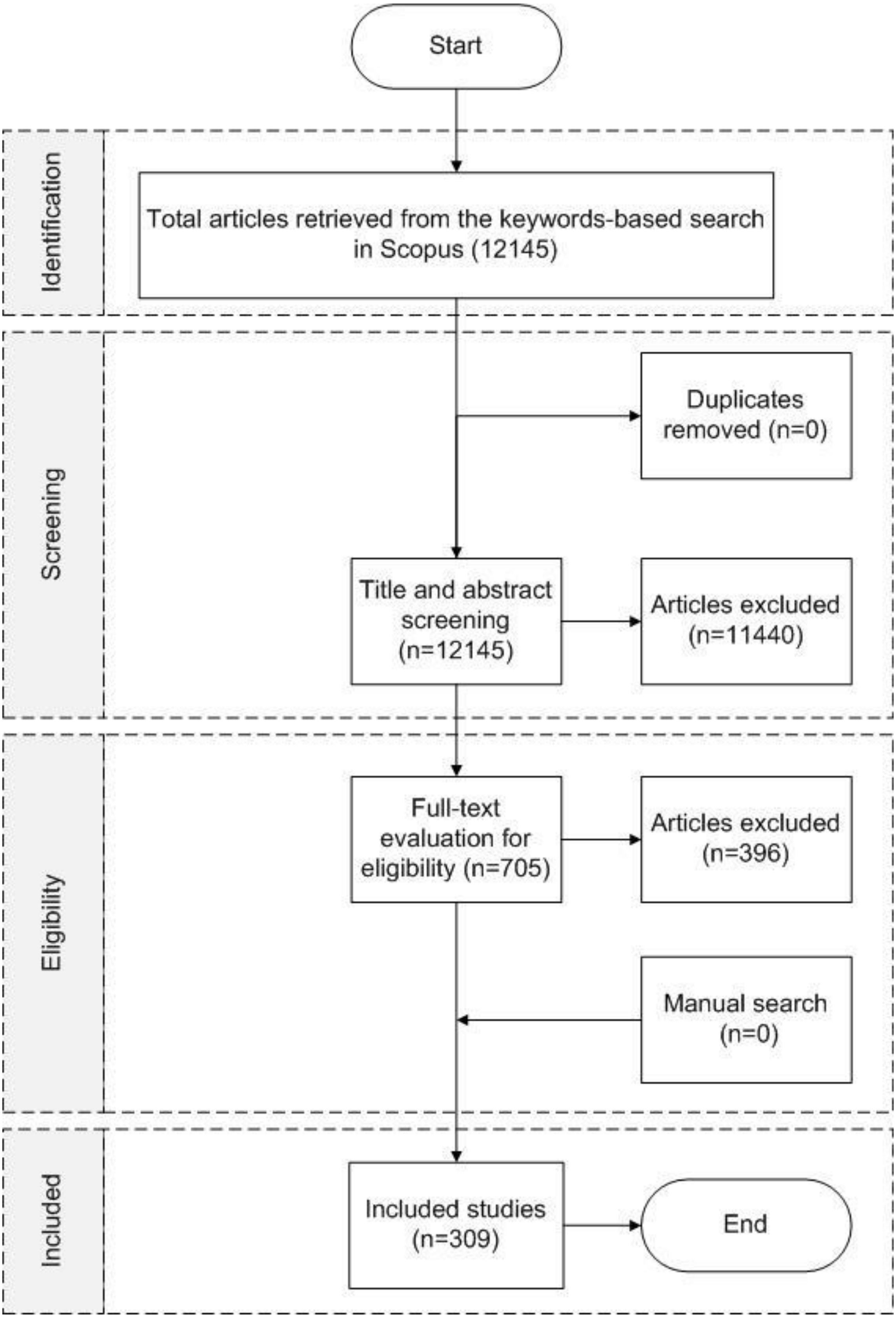


Fig. 2: PRISMA flow diagram of screening and selecting articles.

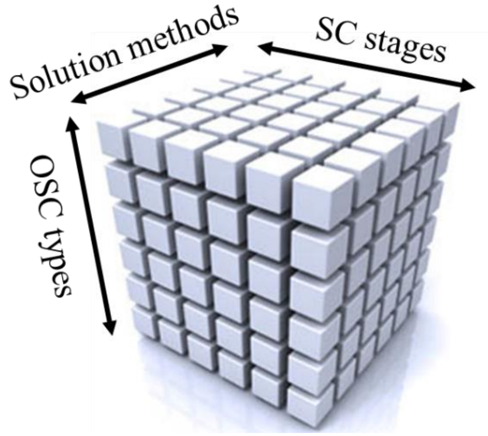


Fig. 3: A schematic diagram of the three-dimensional classification matrix based on off-site construction (OSC) types, solution methods and supply chain (SC) stages.

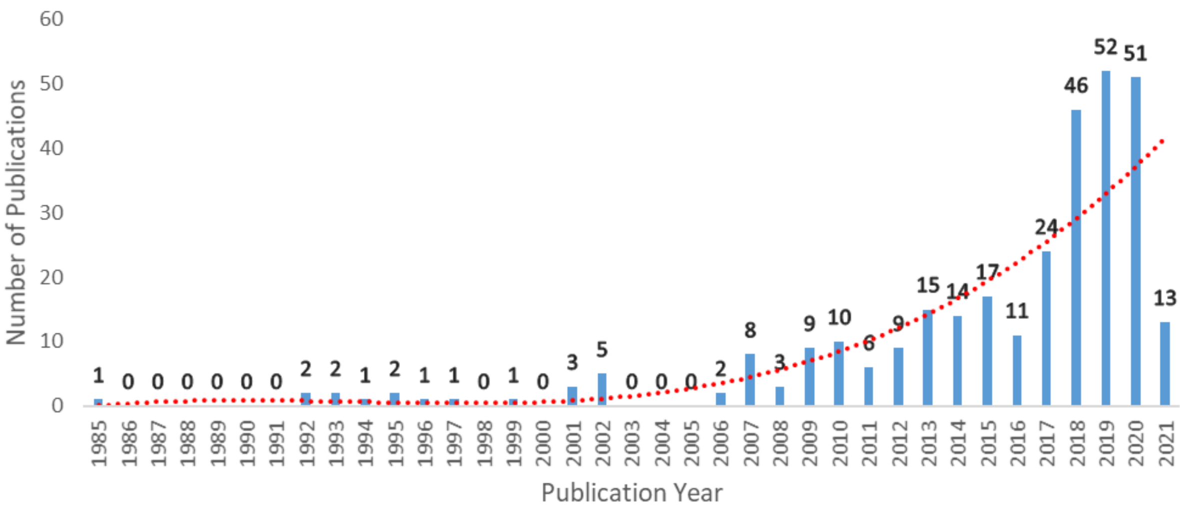


Fig. 4: Annual research publications on off-site construction supply chain management (OSC-SCM).

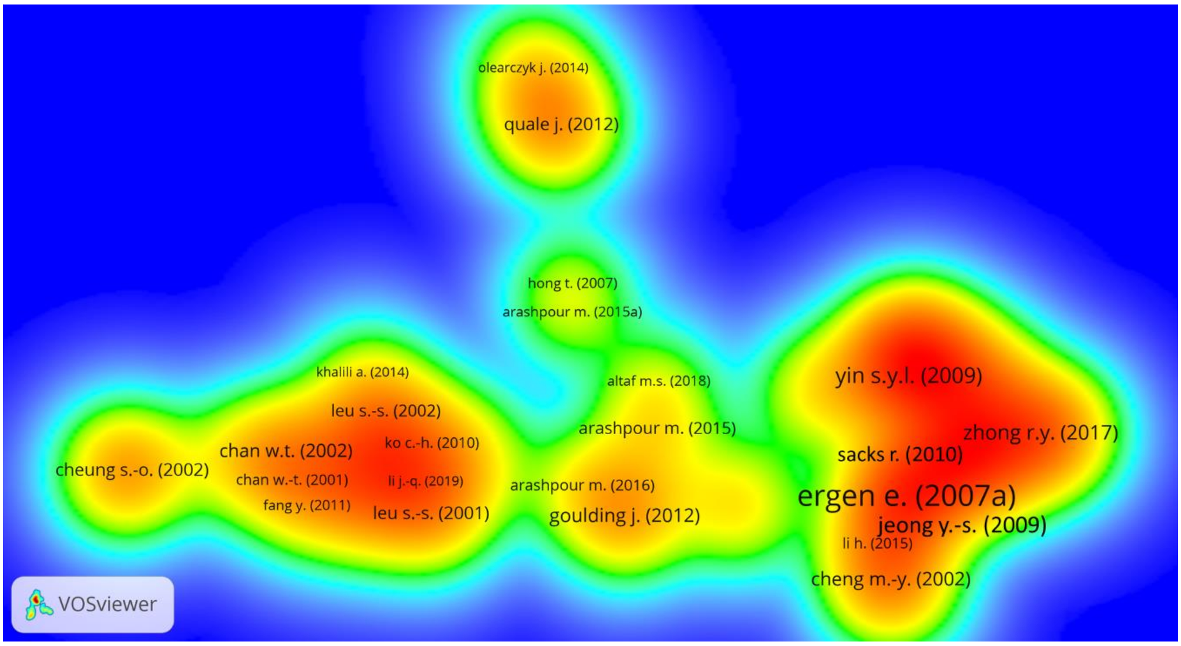


Fig. 5: Density map of articles citation network analysis.

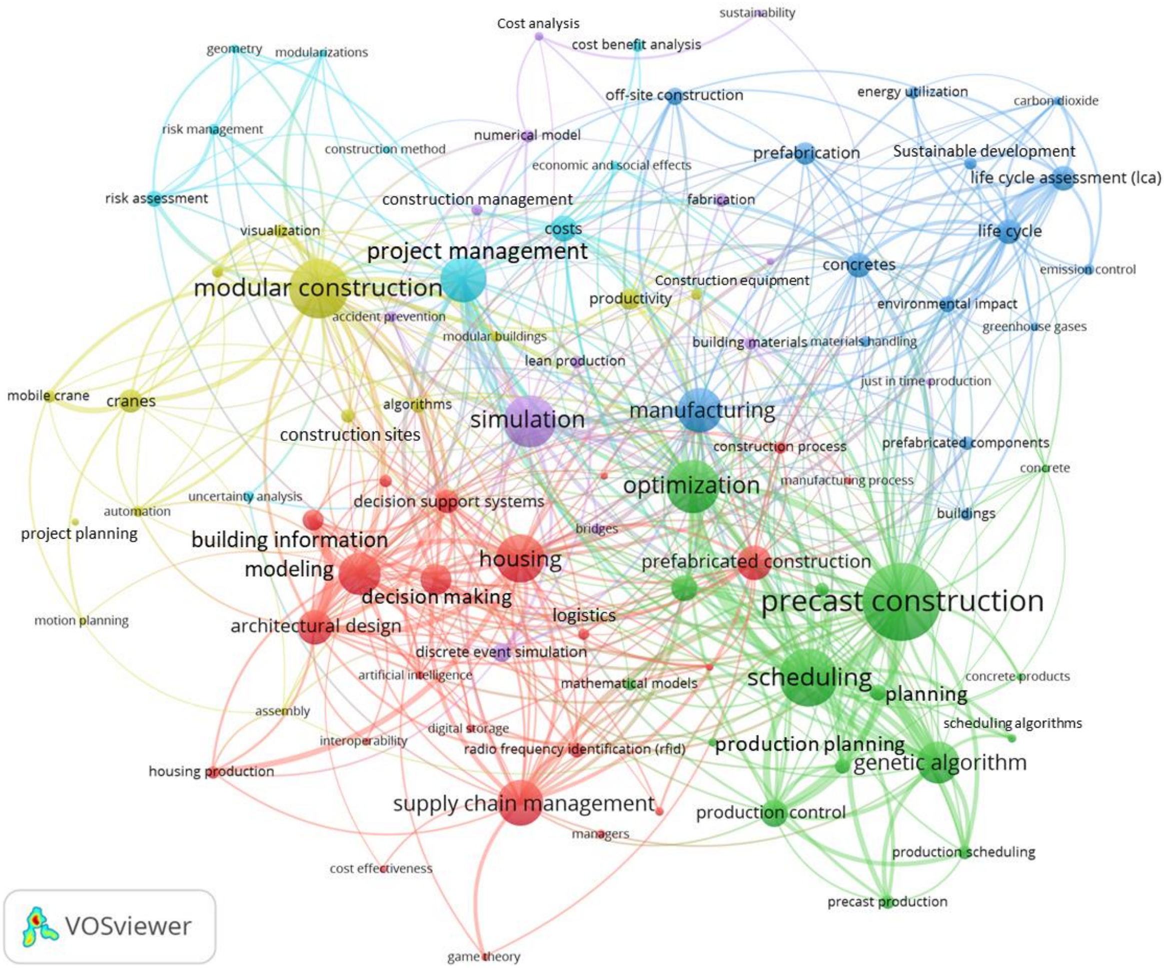
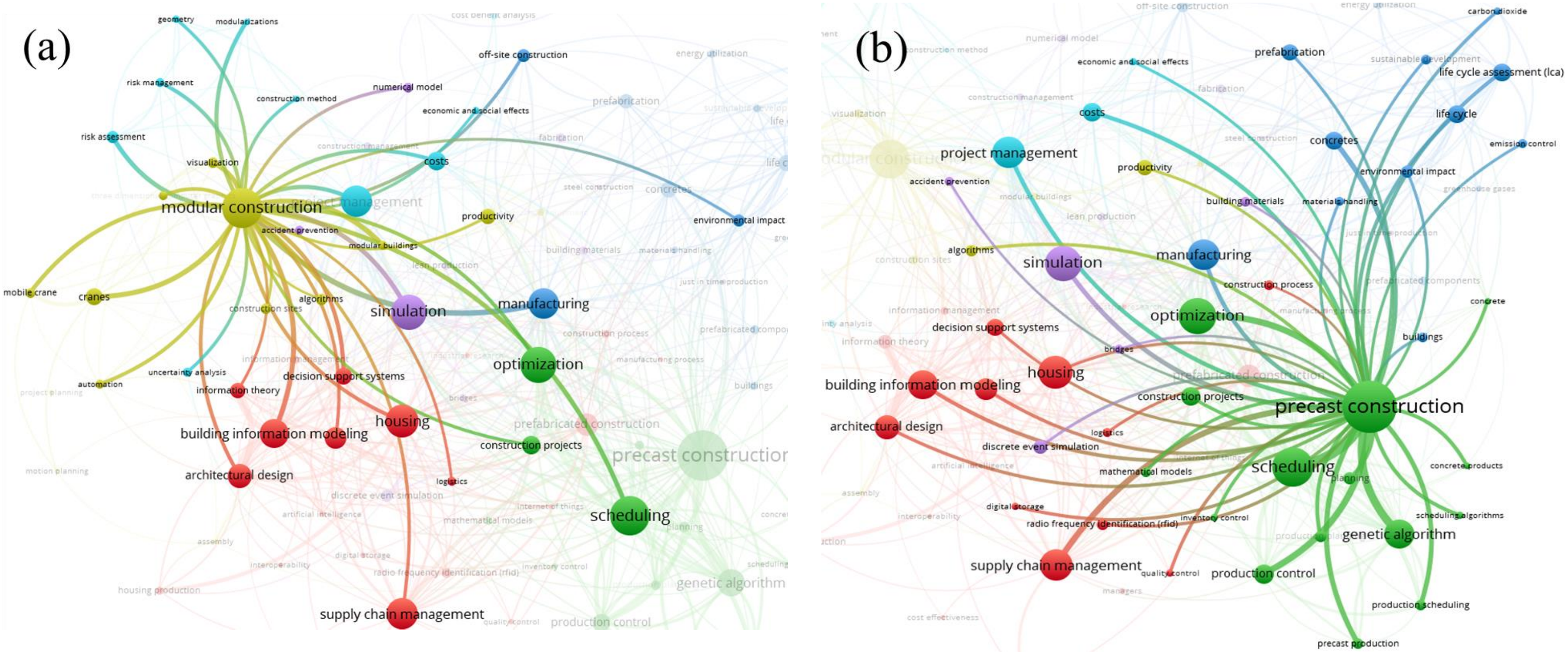
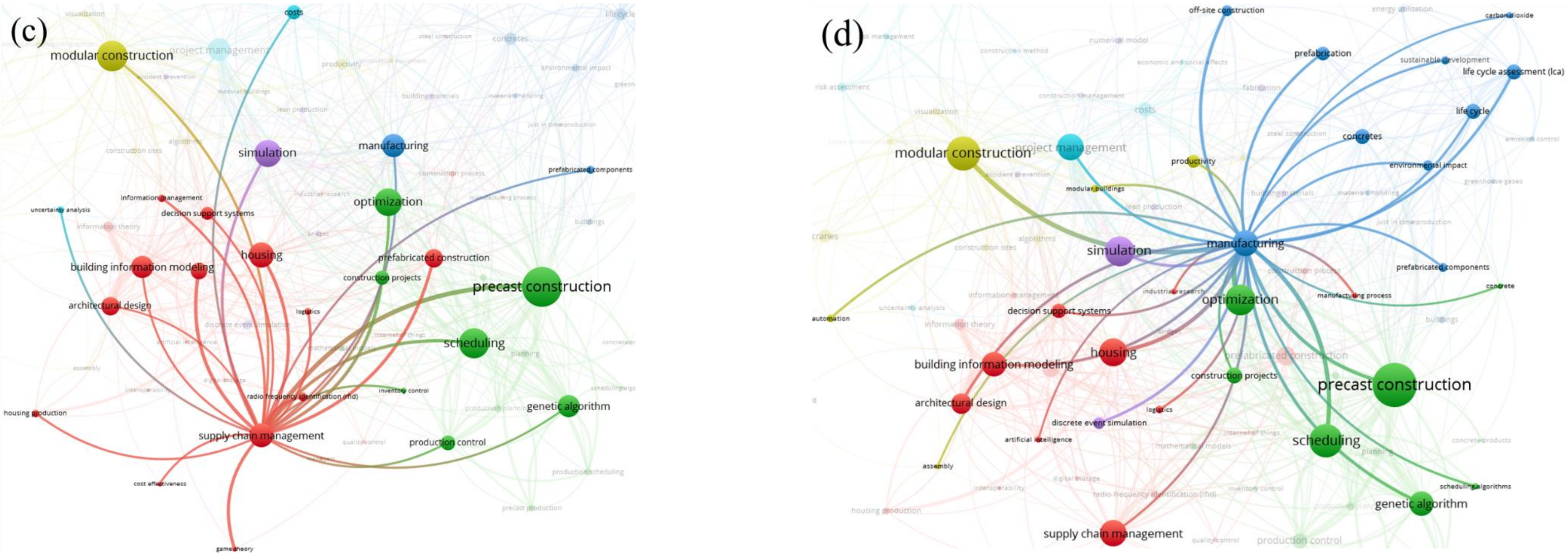


Fig. 6: Co-occurrence network of keywords in OSC-SCM research.



(a)
geometry
modularizations
off-site construction
risk management
construction method
numerical model
economic and social effects
risk assessment
visualization
costs
modular construction
productivity
environmental impact
accident prevention
modular buildings
mobile crane
cranes
algorithms
simulation
manufacturing
optimization
uncertainty analysis
automation
decision support systems
information theory
housing
building information modeling
construction projects
architectural design
logistics
scheduling
supply chain management
(b)
carbon dioxide
prefabrication
economic and social effects
life cycle assessment (lca)
costs
life cycle
project management
concretes
emission control
productivity
environmental impact
accident prevention
building materials
materials handling
algorithms
simulation
manufacturing
construction process
concrete
optimization
decision support systems
buildings
housing
building information modeling
construction projects
precast construction
architectural design
logistics
discrete event simulation
scheduling
concrete products
mathematical models
digital storage
inventory control
scheduling algorithms
radio frequency identification (rfid)
genetic algorithm
supply chain management
quality control
production control
production scheduling
precast production


(c)
modular construction
costs
simulation
manufacturing
optimization
prefabricated components
uncertainty analysis
information management
decision support systems
housing
prefabricated construction
building information modeling
construction projects
precast construction
architectural design
logistics
scheduling
radio frequency identification (rfid)
inventory control
genetic algorithm
housing production
supply chain management
production control
cost effectiveness
game theory
(d)
off-site construction
prefabrication
carbon dioxide
sustainable development
life cycle assessment (lca)
life cycle
concretes
modular construction
project management
productivity
environmental impact
modular buildings
simulation
manufacturing
prefabricated components
industrial research
manufacturing process
concrete
optimization
automation
decision support systems
housing
building information modeling
construction projects
precast construction
architectural design
logistics
discrete event simulation
artificial intelligence
scheduling
assembly
scheduling algorithms
genetic algorithm
supply chain management

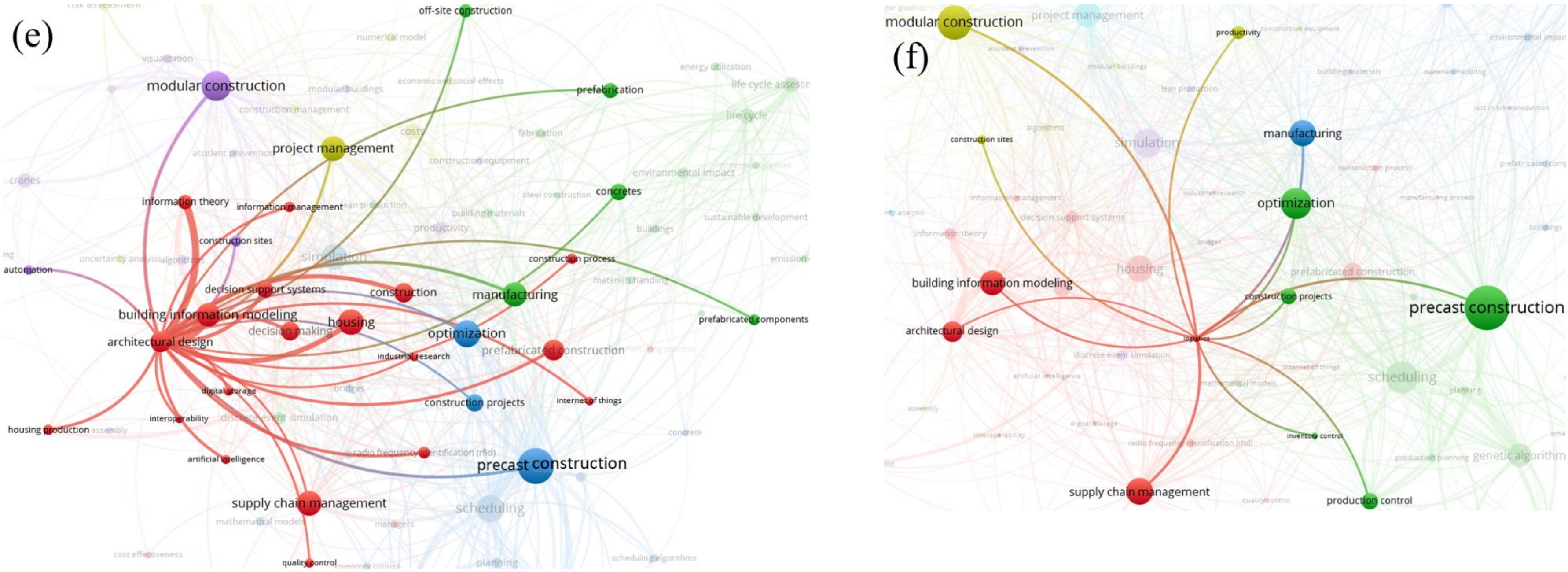


Fig. 7: The keyword networks of: (a) modular construction; (b) precast construction; (c) supply chain management; (d) manufacturing; (e) architectural design; and (f) logistics.

Keywords	Year	Strength	Begin	End	1985 - 2020
scheduling	1985	2.429	**1994**	2005	
production planning	1985	2.3828	**1994**	2006	
genetic algorithm	1985	4.8354	**2001**	2010	
heuristic algorithm	1985	2.094	**2001**	2011	
housing	1985	2.3088	**2007**	2011	
construction industry	1985	2.0196	**2007**	2014	
radio frequency identification	1985	1.9032	**2007**	2009	
industry	1985	1.9104	**2010**	2016	
building	1985	2.8732	**2011**	2014	
algorithm	1985	2.6637	**2012**	2015	
simulation	1985	2.5424	**2012**	2012	
visualization	1985	2.2768	**2012**	2017	
mobile crane	1985	2.7572	**2013**	2015	
energy	1985	2.0326	**2013**	2016	
model	1985	2.8601	**2016**	2017	
hong kong	1985	2.6867	**2017**	2018	
precast construction	1985	2.5999	**2017**	2018	
framework	1985	2.4581	**2017**	2020	
resource	1985	1.8138	**2017**	2017	
bim	1985	2.7003	**2018**	2020	
logistics	1985	2.5152	**2018**	2020	
prefabricated construction	1985	2.1982	**2018**	2020	
internet	1985	2.1462	**2018**	2020	
thing	1985	2.094	**2018**	2018	
technology	1985	2.094	**2018**	2018	
performance	1985	4.1464	**2019**	2020	
prefabrication	1985	3.6972	**2019**	2020	
life cycle assessment	1985	3.2725	**2019**	2020	
greenhouse gas emission	1985	2.2247	**2019**	2020	
prefabricated component	1985	1.9439	**2019**	2020	

Fig. 8: Top 30 keywords with the strongest citation bursts on the modelling of OSC-SC.

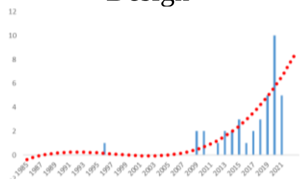
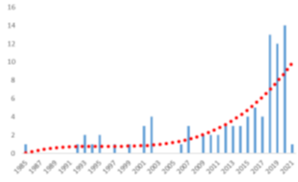
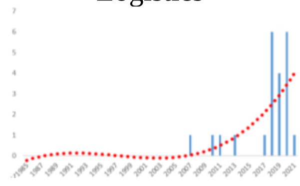
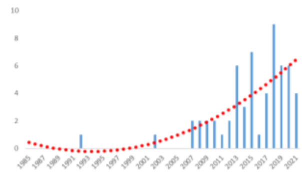
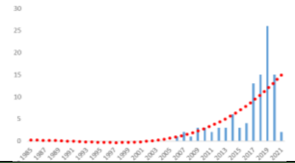
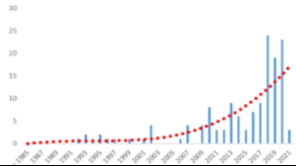
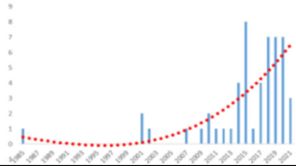
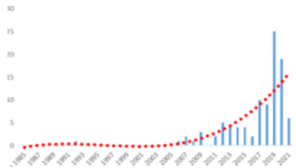
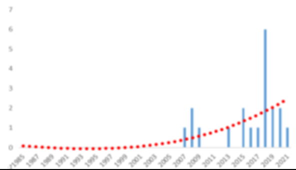
Supply chain stages / Off-site construction types	Design 	Production 	Logistics 	Installation 	Integrated Supply Chain 
Construction-based PCs 	10	52	11	23	45
Panelized Construction 	11	10	6	7	17
MiC 	14	22	4	23	35
Civil Infrastructure 	4	3	1	6	5

Fig. 9: Research trends and 2D classification matrix of OSC-SCM based on OSC types and SC stages.

Solution methods \ Supply chain stages	Design	Production	Logistics	Installation	Integrated Supply Chain
Optimization	10	34	7	8	12
Simulation	3	13	3	11	7
LCA	0	1	0	1	19
BIM	10	5	3	7	2

Fig. 10: Research trends and 2D classification matrix of OSC-SCM based on solution methods and SC stages.

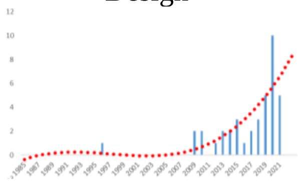
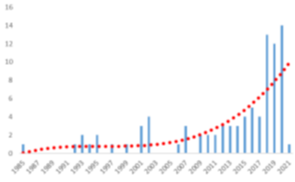
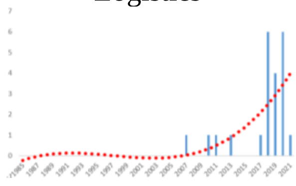
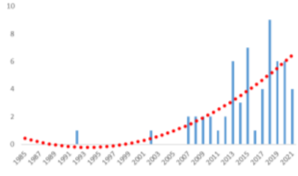
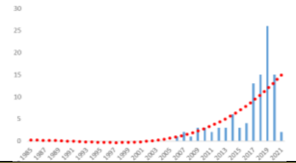
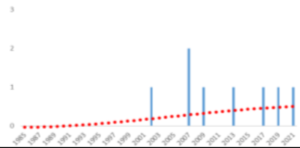
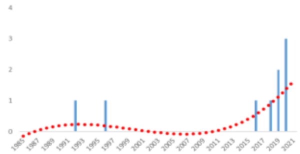
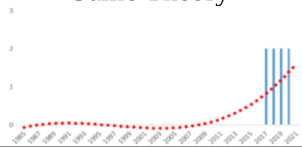
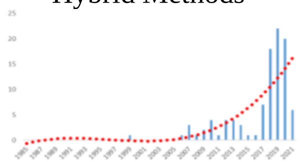
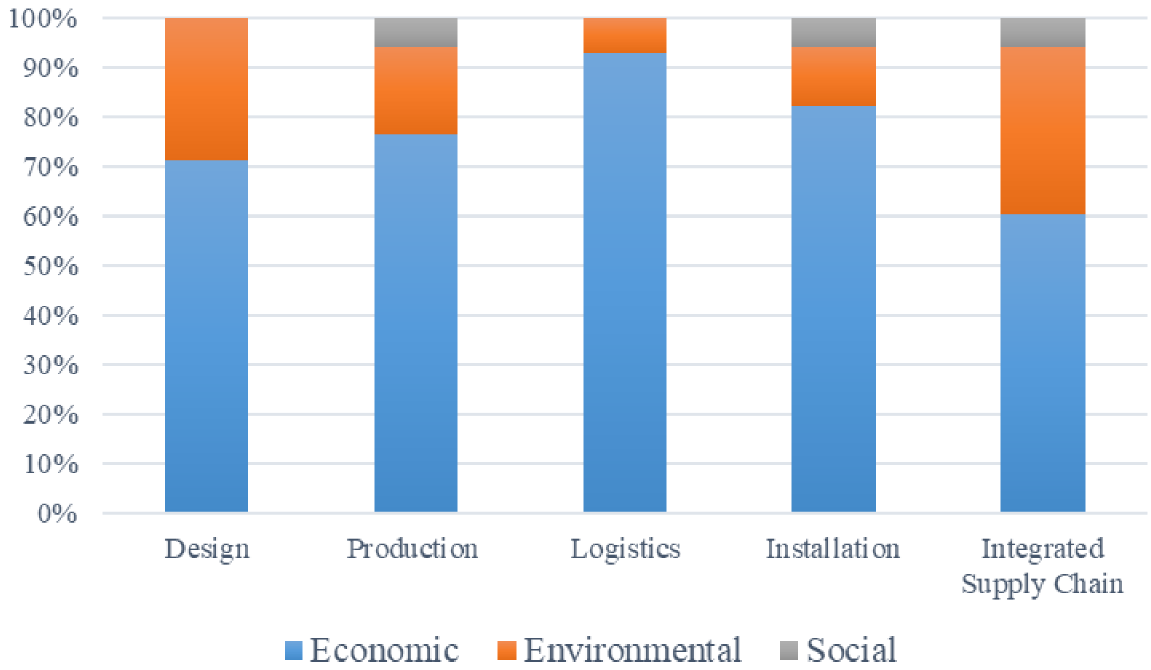
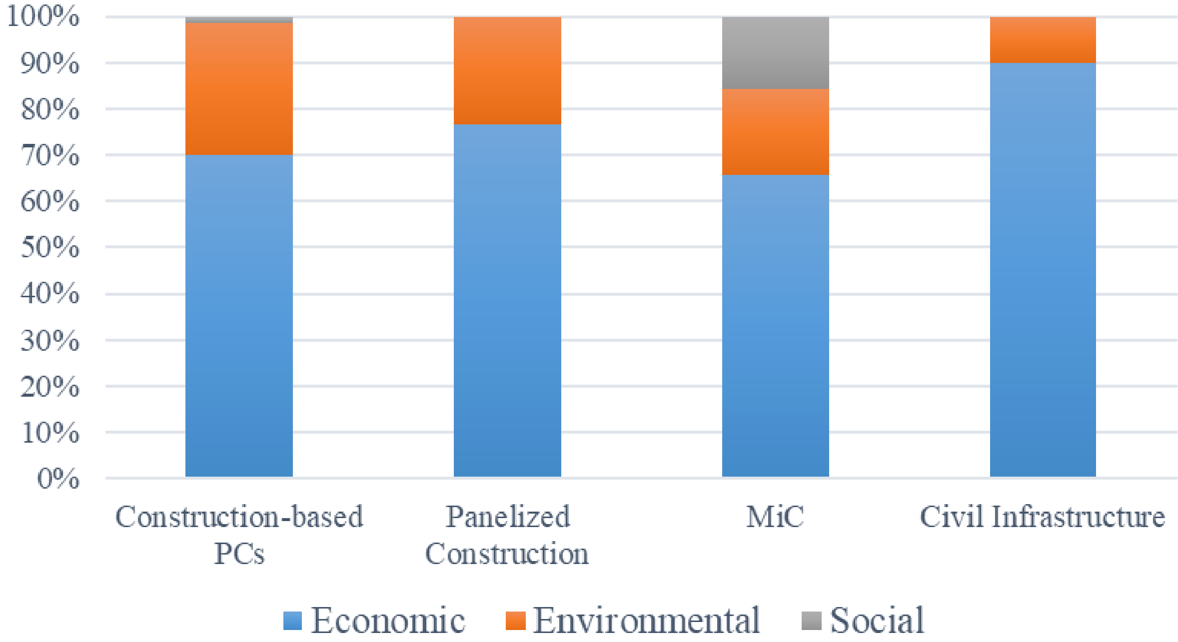
Supply chain stages / Solution methods	Design 	Production 	Logistics 	Installation 	Integrated Supply Chain 
PTS 	0	1	3	1	3
AI 	1	5	1	2	1
Game Theory 	1	1	0	0	6
Hybrid Methods 	9	24	2	26	37

Fig. 10: Research trends and 2D classification matrix of OSC-SCM based on solution methods and SC stages (Cont.).

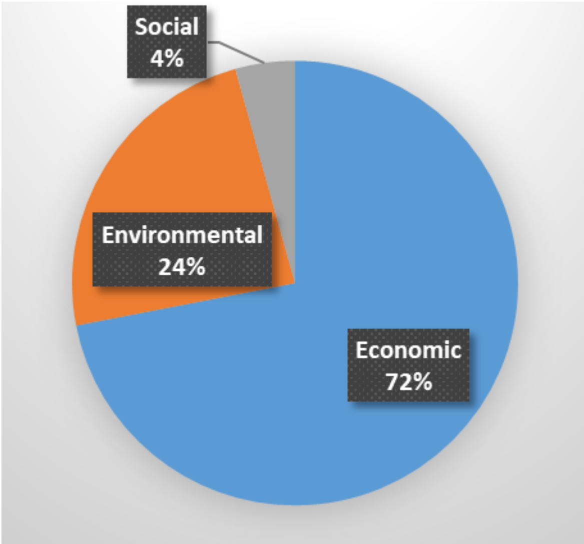


(a) Distribution of the three sustainability dimensions considered in each OSC-SC stage.

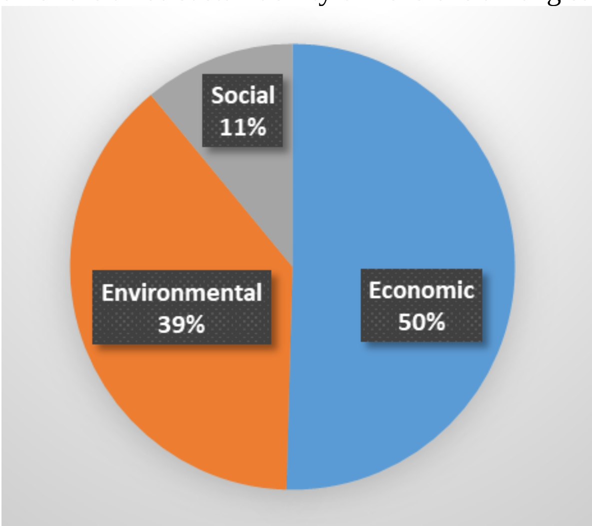


(b) Distribution of the three sustainability dimensions considered in each OSC type.

Fig. 11: The percentage of consideration of the three sustainability dimensions addressed in previous studies on the modelling of OSC-SC.



(a) Distribution of the three sustainability dimensions among studies on OSC-SC.



(b) Distribution of the three sustainability dimensions among studies on other supply chains, adapted from (Rajeev et al., 2017).

Fig. 12: The difference between the distribution of the three sustainability dimensions in OSC-SC and the other supply chains.

	Construction-based PCs	MiC	Panelized Construction
Design Stage	• Contract management during construction and operating phases. • Integrate additive manufacturing solutions to increase customization while maintaining standardization.	• Integrate the knowledge of design teams and supply chain members into one data repository to ensure the suitability of potential designs to all MiC stakeholders. • Develop decision support systems to evaluate potential designs based on the three sustainability factors.	• Data interoperability between BIM tools of architectural designers, structural designers and manufacturers.
Production Stage	• Develop benchmark instances for the flow shop sequencing problem of production of PCs to evaluate the computational efficiency of the proposed optimization approaches. • Reactive and real time production planning based on the rolling horizon strategy to mitigate the impact of production uncertainties. • Horizontal collaborative planning to enable win-win collaboration among prefabricators. • Sustainable production planning.	• Dynamic and agile production planning to respond to disturbances at the production stage in real-time. • Sustainable production planning. • Application of robotics and Industry 4.0 technologies. • Develop benchmark instances for the flow shop sequencing problem of MiC production to evaluate the proposed metaheuristics' performance.	• Formulate the production scheduling as a stochastic-based model, while considering the uncertainty of production time and number of workers. • Integrate the production scheduling and resources allocation problems. • Develop hybrid metaheuristics to improve the searching mechanism of single metaheuristics.
Logistics Stage	• Dynamic logistics planning and control by considering disturbances at the logistics stage. • Develop sustainable and collaborative strategies between transporters when serving multiple construction sites.	• Develop optimization models for the vehicle routing and truck dispatching problems with considering different vehicle types and different traffic levels. • Selection of optimum transportation mode in case of modules produced overseas with considering its economic and environmental impacts. • Find the optimum location of the consolidation center and optimize its inventory management. • Evaluate the impact of lean techniques to MiC logistics management. • Proactive logistics planning and control by predicting potential disturbances at the logistics stage and responding to them.	• Develop optimization models for the vehicle routing and truck dispatching problems with considering different vehicle types and different traffic levels. • Evaluate the impact of lean techniques, including JIT, on delivery KPIs (e.g. on-time delivery, costs, sustainability impact, etc.). • Develop machine learning approaches to estimate costs and sustainability impact of logistics activities by using real-time data collected from sensors.
On-site Construction Stage	• Evaluation of lean construction techniques on project KPIs such as productivity, project's duration, cost, safety, etc. • Scheduling optimization of crane operations and other construction activities simultaneously. • Proactive risk response approaches to predict potential disruptions and propose the optimum risk response actions.	• Scheduling optimization of crane operations and other construction activities simultaneously. • Site layout planning of high-rise MiC projects in dense urban areas. • Systematic risk management at MiC sites to identify, assess and respond to potential risks. • Evaluate the impact of lean techniques to reduce wastes at the construction stage.	• Linking 3D BIM with kinematic software to solve the crane location problem. • Use data analytics techniques like cascaded neural network rather than expert-based estimation to predict the activity durations. • Consider the hazardous related to humans while modeling the site construction.
Integrated supply chain Stage	• Operational problems at each supply chain stage (e.g. resource allocation, inventory planning, despatching time, etc.) need to be integrated to reach a mutually beneficial supply chain. • Proactive supply chain risk management to predict and respond to potential risks.	• Integrating IoT and blockchain to enhance information sharing, traceability and security. • Optimization of the supply chain performance with considering sustainability factors. • Holistic risk management DSS to identify, assess and respond to potential risks along the stages of the MiC supply chain. • Robust optimization of the supply chain performance with considering different uncertainties.	• Consider more sustainability factors like social impacts when optimizing the SC performance. • Optimize coordination between SC stages to achieve win-win collaboration between its partners.

Fig. 13: Future research opportunities in the modelling of OSC-SC.

Table 1: Bibliometric ranking of journals based on the number of modelling studies.

Journal	No. of studies	Total citations	Norm. citations	Total link strength
Automation in Construction	79	2155	101.74	206
Journal of Cleaner Production	28	351	38.26	63
Journal of Construction Engineering and Management	26	391	14.88	67
Sustainability (Switzerland)	16	91	6	42
Journal of Computing in Civil Engineering	12	214	8.02	38
International Journal of Production Research	9	101	11.64	33
Construction Management and Economics	8	115	12.78	32
Advanced Engineering Informatics	6	155	6.09	15
Canadian Journal of Civil Engineering	6	92	3.12	30
Advances in Civil Engineering	5	10	1.96	20

Table 2: Top researchers on the modelling of OSC-SC.

Author	No. of Studies	No. of citations	TLS	Norm. Citations	Author	No. of Studies	No. of citations	TLS	Norm. Citations
Al-Hussein M.	22	419	15	24.65	Xue F.	8	312	23	17.07
Hu H.	12	281	8	20.44	Huang G.Q.	7	122	7	9.25
Hermann U.	11	169	18	7.03	Hong J.	6	173	12	12.5
Taghaddos H.	11	165	18	6.89	Xu G.	6	106	9	11.54
Shen G.Q.	10	265	25	16.05	Abbasi B.	5	96	8	6.46
Arashpour M.	9	185	10	17.52	Ko C.-H.	5	128	0	3.26
Li C.Z.	9	241	24	14.12	Lei Z.	5	141	13	4.75
Li X.	9	105	15	9.36	Lu W.	5	141	7	7.54
Wang Z.	9	120	8	17.29	Wakefield R.	5	173	8	8.08
Lu M.	8	146	1	5.89	Zhong R.Y.	5	192	11	10.68

TLS: Total link strength.

Table 3: Top-cited articles on the modelling of OSC-SC.

Article	No. of citations	No. of links	Norm. citations
(Monahan and Powell, 2011)	257	1	3.27
(Ergen et al., 2007a)	172	3	3.75
(Mao et al., 2013)	150	1	4.94
(Garrido et al., 2008)	126	0	2.42
(Jeong et al., 2009)	108	2	2.6
(Yin et al., 2009)	100	9	3.32
(Babič et al., 2010)	91	0	3.66
(Zhong et al., 2017)	90	4	4.65
(Sacks et al., 2010)	89	3	3.05
(Kim et al., 2015)	80	1	2.74

Table 4: Classification of design problems and the applied solution methods in the construction-based prefabricated components (PCs).

Problem \ Method	Optimization	BIM	AI	Game Theory	DSM	Hybrid
Contract Management	0	0	1	1	0	0
Design for Economic Supply Chain	0	0	0	0	0	1
Design for Lean Construction	0	0	0	0	0	1
Structural Design	2	0	0	0	0	1
Architectural Design	0	1	0	0	0	0
Design for Waste Reduction	0	0	0	0	1	0
Design Information Exchange	0	0	0	0	0	1

BIM: Building information modelling; AI: Artificial intelligence; and DSM: Design structure matrix.

Table 5: Summary of PC production studies based on problem type and methodology type.

Problem \ Method	Opt.	Sim.	BIM	Game T.	AI	LCA	Hybrid M.	Other M.
Production Scheduling	9	3	0	0	1	0	3	0
Resource allocation	1	0	0	0	1	0	1	0
Production scheduling & resource planning	10	0	0	0	0	0	2	0
Lean production	0	2	0	0	0	0	1	0
Green production	0	0	1	1	1	1	2	1
Production layout	2	0	0	0	0	0	1	0
Production control	1	1	1	0	0	0	0	0
Others	0	1	1	0	0	0	1	2

Opt.: Optimization; Sim.: Simulation; Game T.: Game theory; AI: Artificial intelligence; LCA: Life cycle assessment; Hybrid M.: Hybrid methods; and Other M.: Other methods.

Table 6: Classification of studies on the logistics stage of PCs.

Problem \ Method	Optimization	BIM	Simulation	PTS	Hybrid methods
Inventory Management	1	0	0	0	2
Procurement Management	0	1	0	0	0
Route Planning	1	0	0	0	0
Lean Logistics	0	1	0	0	0
Others	2	0	1	2	0

BIM: Building information modelling; and PTS: Positioning and tracking systems.

Table 7: Classification of studies on the on-site assembly stage of PCs.

Problem \ Methods	Optimization	Simulation	BIM	PTS	LCA	Empirical Eqs.	Structural analysis	AI	Hybrid methods
Crane Operation & Planning (COP)	3	0	0	0	0	0	1	0	3
Risk Management	0	3	0	0	0	0	0	0	2
Project Scheduling & Resource Planning	0	0	0	0	0	0	0	0	2
Productivity Assessment	0	2	0	0	0	1	0	0	0
Green Construction	0	0	0	0	1	0	0	0	1
Others	0	0	2	1	0	0	0	1	0

BIM: Building information modelling; PTS: Positioning and tracking systems; LCA: Life cycle assessment; Empirical Eqs.: Empirical equations; and AI: Artificial intelligence.

Table 8: Classification of studies on prefabricated supply chain based on problem types and solution methods.

Problem \ Method	Opt.	Sim.	PTS	Hybrid	Game	SNA	AI	LCA	GHG	ABC	Cloud
SC Performance	5	0	0	3	0	0	0	0	0	1	0
Collaborative SC	1	0	0	1	6	1	0	0	0	0	0
SC Information Management	0	0	1	5	0	0	0	0	0	0	1
Tracking	0	0	2	1	0	0	0	0	0	0	0
SC Risk Management	0	1	0	0	0	2	0	0	0	0	0
Green SC	0	0	0	3	0	0	0	5	1	0	0
Sustainable SC	0	1	0	0	0	0	0	0	0	0	0
Others	0	0	0	2	0	0	1	0	0	1	0

Opt.: Optimization; Sim.: Simulation; Game: Game theory; SNA: Social network analysis; AI: Artificial intelligence; LCA: Life cycle assessment; GHG: greenhouse gas emissions; ABC: Activity-based costing; and Cloud: Cloud computing.

Table 9: Classification of design problems in the panelized construction and the applied research methods.

Problem \ Method	Optimization	BIM	MCDM	Hybrid Methods
Architectural Design	0	3	1	1
Structural Design	2	0	0	0
Thermo-economic Design	3	0	0	0
Lean Design	0	1	0	0

BIM: Building information modelling; and MCDM: multi-criteria decision making.

Table 10: Summary of panel production studies based on problem types and solution methods.

Problems \ Methods	Optimization	Simulation	Positioning and tracking systems	Hybrid Methods
Production Scheduling	5	1	0	1
Resource allocation	1	1	0	0
Quality Inspection	0	0	1	0

Table 11: Summary of transportation and delivery studies based on problem types and solution methods in panelized construction.

Problems \ Methods	Optimization	Simulation	BIM
JIT delivery	1	2	0
Transportation planning	2	0	1
BIM: Building information modelling.			

Table 12: Summary of on-site construction studies based on problem types and solution methods panelized construction.

Problems \ Methods	Optimization	Simulation	BIM	Hybrid Methods
Crane planning	0	0	0	1
Construction scheduling	2	0	0	0
Construction site modelling	0	1	2	0
Construction progress monitoring	0	0	0	1
BIM: Building information modelling.				

Table 13: Summary of integrated supply chain studies based on problem types and solution methods panelized construction.

Problems \ Methods	Optimization	BIM	LCA	Cost analysis
Integrated supply chain	1	1	0	0
Green supply chain	0	0	8	0
Others	0	4	0	3
BIM: Building information modelling; and LCA: Life cycle assessment.				

Table 14: Classification of design problems in MiC and the applied modelling methods.

Problem \ Method	BIM	FEM	DSM	Hybrid
Architectural Design	1	0	1	1
Design Information Exchange	1	0	1	0
Structural Design	0	5	0	1
Automation in Design	2	0	0	1
BIM: Building information modelling; FEM: Finite element analysis; and DSM: Design structure matrix.				

Table 15: Classification of studies on MiC production based on problems and research methods.

Problems \ Methods	Optimization	Simulation	BIM	AI	Hybrid Methods

Resource Planning	1	1	0	0	2
Production Scheduling	1	0	0	0	0
Facility Layout	0	0	0	0	1
Integrated Problems	1	1	1	0	1
Ergonomic Analysis	0	0	1	1	0
Lean Production	0	2	0	0	1
Quality Inspection	0	0	0	0	3
Others	0	0	0	1	3

BIM: Building information modelling; and AI: Artificial intelligence.

Table 16: Classification of studies on MiC installation stage based on problems and research methods.

Problems \ Methods	Algorithm	Optimization	Simulation	BIM	FEM	AI	Hybrid
Crane Operation & Planning	1	2	0	3	1	0	8
Project Scheduling & Resource Planning	0	0	0	0	0	1	1
MEP Modules-related Problems	0	0	0	0	0	0	2
Lean Construction	0	0	0	0	0	0	1
Site Progress Monitoring	0	0	0	0	0	0	1
Others	0	0	1	0	0	0	1

BIM: Building information modelling; FEM: finite element method; and AI: Artificial intelligence.

Table 17: Classification of studies on multiple stages in the MiC SC based on problems and research methods.

Problems \ Methods	Optimization	Simulation	BIM	LCA	Hybrid
SC Performance	3	1	1	0	3
SC Risk Management	1	0	0	0	9
Lean SC	0	1	0	0	1
Green SC	0	0	0	5	0
Sustainable SC	0	0	0	1	2
Information Sharing	0	0	0	0	3
Others	1	2	1	0	0

BIM: Building information modelling; and LCA: Life cycle assessment.