A Holistic Review of off-site Construction Literature Published between 2008 and 2018

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Abstract

Off-site construction (i.e., OSC) has become an emerging research domain in the recent decade. Through a three-step holistic review approach incorporating bibliometric search, scientometric analysis, and in-depth qualitative discussion, this study contributes to the body of knowledge in OSC by critically reviewing and summarizing: 1) the latest research keywords and main research topics in OSC; 2) the performance of OSC compared to that of conventional construction approach; 3) current research gaps in integrating OSC with other emerging construction concepts; and 4) future research directions in OSC. OSC is a domain that can be extended to cross-disciplinary research from the perspectives of engineering, management, and technology. Existing research have been focusing on many research disciplines, such as structural behaviors and joint connections of prefabricated components, scheduling and planning of off-site activities, as well as performance evaluation of OSC. However, further research is needed in integrating the emerging digital construction technology, integrated project delivery method, lean construction, and issues of sustainability of OSC. There are still limited studies linking OSC to the concept of Design for Manufacturing and Assembly. Future research should also adopt a larger database and allow for comprehensive evaluation of OSC performance.

Keywords: Off-site construction (OSC); prefabrication; scientometric analysis; science mapping; literature review.

1. Introduction

Off-site construction (OSC) offers a new construction approach by moving the building construction process away from the jobsite into a controlled factory environment (Jiang et al., 2018). Though OSC is still at the early stage of its application in developing countries (e.g., China) (Hong et al., 2018), this emerging construction technique has stimulated wide public attention due to its potential advantages in achieving better project performance, such as reducing project duration and minimizing construction waste. Multiple studies have compared the performance between OSC and conventional construction methods in terms of cost (Hong et al., 2018), energy performance (Hong et al., 2016), and overall sustainability of the process (Kamali and Hewage, 2017). OSC involves the modularity of construction products, which is related to design, manufacture, supply chain, and the life cycle assessment (Sonego et al., 2018). These contemporary construction issues, comprised of Building Information Modeling (BIM), integrated project delivery (IPD), and environmental sustainability have already gained increasing attention in both academia and industry. Accompanying these contemporary issues, OSC, by its nature is not isolated from them. As more studies are being published in the domain of OSC, there is a further need to gain answers to certain key questions, including but not limited to: 1) What are the latest research topics within OSC? 2) How is OSC performing compared to traditional construction methods? 3) Have IPD, BIM, and other construction concepts (e.g., lean) been integrated into OSC? and 4) What are the main trends and near-future directions in OSC(e.g., OSC linked to lean and BIM)? The following sections of this review paper are structured as: Section 2 provides the rationale of this review-based research; Section 3 describes the research methodology; Section 4 shows the results of bibliometric search and scientometric analysis; Section 5 extends the science mapping results into in-depth qualitative discussion; and finally Section 6 concludes this review-based study. The findings are demonstrated in sections 4, 5, and 6 and respond directly to the above research questions.

2. Motivation of the Research

Literature review is considered as an expedient approach to gain in-depth understanding of a research domain (He et al., 2017), such as the performance of OSC compared to traditional construction, and integration of OSC with other emerging construction concepts in this study. A thorough review of existing literature published in the OSC domain, such as Pan and Sidwell (2011), Li et al. (2014), Gasparri et al. (2015), Tam et al.(2015), and Mann (2017), could provide insights addressing these aforementioned research questions. Hosseini et al. (2018) reviewed the OSC literature over the period 1975-2017. However, it is still unclear to point out the latest research topics within the OSC community, especially in the more recent decade. Recent studies such as Hong et al. (2018) focused on the cost performance of OSC projects but based on a limited project sample. Hence, a comparative study of the performance of OSC projects and traditional site construction is needed, ideally with a larger sample. Emerging construction technologies and delivery methods, such as BIM (Abanda et al., 2017; Lee and Kim, 2017), IPD (Nawi et al., 2014; Osman et al., 2017) and lean (Nahmens and Ikum, 2012; Yu et al., 2013) have been discussed in the OSC projects. Nevertheless, it remains unclear how these concepts or methods could be integrated to enhance the performance of OSC projects.

More recent review-based studies in OSC, such as Li et al. (2014) and Mostafa et al. (2016), have been based on manual reviews that might be prone to subjectivity and restricted in their lack of reproducibility (Hammersley, 2001; Markoulli et al., 2017). Consequently, Hosseini et al. (2018) addressed this gap by introducing the scientometric analysis into the review of OSC. The main motivation of this study was to propose a more holistic approach embedded with a more in-depth qualitative discussion to the existing scientometric analysis-based studies. Several recent scientometric analysis-based reviews, including Hosseini et al.'s (2018) work in OSC, Zhao et al.'s (2017) work in BIM, and Song et al.'s (2016) work in PPP, were limited to the scientometric analysis itself only, without engaging thorough discussions to reveal more depth information or implications to a wider readership. Further discussions such as the current mainstreamed research themes, limitations, and framework for future directions were not provided. These aforementioned scientometric analysis-based reviews were limited to self-exploratory topics for discussions such as the most productive scholar, the upmost influential journal, and most frequently searched keywords. Apparently, the level of details presented in aforementioned review papers could be enhanced. For example, the findings of Hosseini et al. (2018) can be extended to open in-depth discussions (e.g., future research directions) following the science mapping of OSC-related publications.

Therefore, a more holistic approach incorporating multiple steps are proposed to provide a more comprehensive picture of the current status, research gaps, and proposed research directions for OSC. By adopting a more holistic approach, this study aims to achieve these objectives: 1) to adopt a bibliometric search to identify the latest research topics in the domain of OSC within the recent decade; 2) to summarize the performance of OSC compared to the traditional construction methods from the selected literature sample;3) to reveal the current gaps in OSC research such as the isolation between OSC and BIM, as well as that between OSC and lean construction (Eastman et al., 2011; Hosseini et al., 2018); and 4) to provide a further framework on recommendations for future research in OSC.

3. Methodology

This study introduced a multi-step holistic review approach in addressing the pre-defined research questions related to the latest research themes in OSC, the overall performance of OSC, integration of OSC with other emerging construction concepts, as well as the trends of OSC research. It integrated the review steps from earlier studies in OSC including Li et al. (2014), Mostafa et al. (2016), and Hosseini et al. (2018). This holistic review further provides a framework linking existing research areas within OSC to near-future research directions, encouraging more interdisciplinary research involving related research areas.

Main research questions were firstly initiated from collective efforts, including pilot study, workshops, seminars, conferences, industry magazines such as Construction Manager by Charted Institute of Buildings (2018), meeting and interviewing industry professionals involved in OSC projects. After two rounds of group discussion among the research team, a consensus were reached on these four aforementioned research questions. They were presentative among the existing literature in OSC. For example, existing studies have been focusing on the safety and sustainability performance (e.g., Fard et al., 2017) of OSC projects. The integration between BIM and OSC has been emphasized (e.g., Li et al., 2018).

The continued study then adopted a holistic approach in reviewing the state-of-the-art research of OSC in the recent decade. The initial phase was a bibliometric review of journal articles, followed by the science mapping of the literature sample, and then the qualitative discussion of research themes in OSC. The workflow of this review-based study is illustrated in Fig.1.

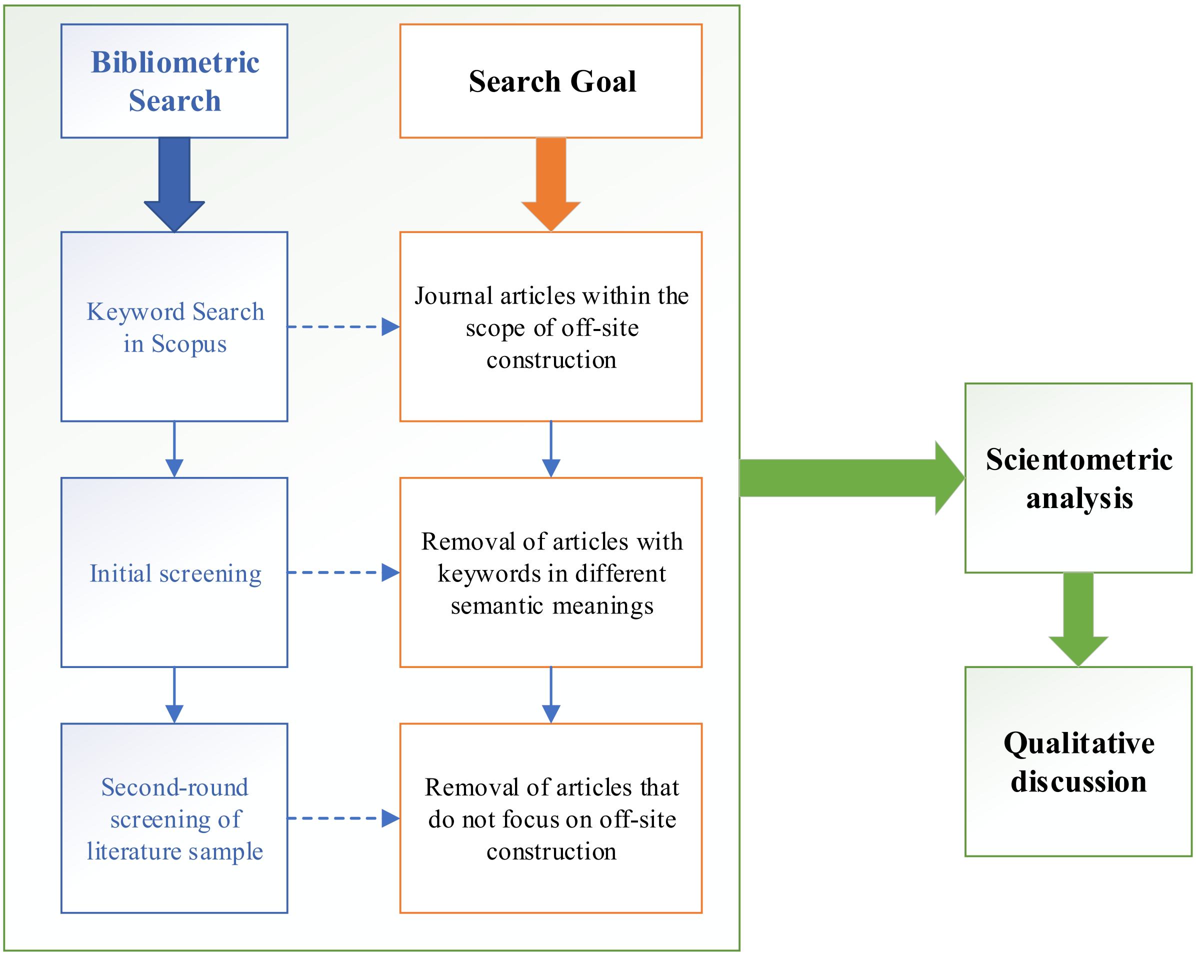


Fig.1. The workflow of OSC review in this study

As shown in Fig.1, a systematic approach was adopted consisting of three steps, namely bibliometric search, scientometric analysis, and qualitative discussion. The bibliometric search comprised of three sub-steps to scoping the literature that fall into the scope of OSC research. Based on the finalized literature sample, science mapping assisted by text mining was adopted to analyse the key findings (e.g., main research keywords) in the literature. Finally, this study extended science mapping (i.e., bibliometric research and scientometric analysis) by providing further discussions on the pre-defined research questions. A detailed description of these three steps are provided in the following subsections.

3.1.Bibliometric search

Bibliometric search of OSC literature was performed in *Scopus*, which has been described by AghaeiChadegani et al. (2013) as the search engine covering more journals and more recent publications compared to any other available digital sources (e.g., *Web of Science*). *Scopus* was also recommended by other studies (Heet al., 2017;Oraeeet al., 2017; Hosseini et al., 2018) within the construction and project management fields. In the domain of OSC, a wide range of interchangeable terms have been used (Maoet al. 2015), such as ‘prefabricated construction’ or ‘modular construction’. By reviewing earlier studies (e.g., Pan and Goodier, 2012; Caoet al., 2015; Maoet al., 2015; Hosseini et al. 2018).Keywords in OSC research were selected based on the thorough review of these previous relevant papers regarding the definition and concepts of OSC. A list of terms for OSC that were used interchangeably were noted as keywords. They have comprehensively covered the definitions of OSC, and allow a wide range of OSC papers to be initially included. The bibliometric research was set initially by inputting keywords in *Scopus* denoted below:

TITLE-ABS-KEY(“Off-site construction” OR “off site construction” OR “prefabricated construction” OR “industrialized building” OR “panelized construction” OR “modular construction” OR “tilt up construction” OR “offsite construction” OR “precast construction” OR "tilt-up construction" OR "off-site manufacturing" OR "prefabrication construction")

Moreover, all associated journal papers published in English in the recent decade (i.e., from 2008 to 2018) were selected for this study. Only literature in OSC published in the last decade were included due to two reasons: first, this study aimed to investigate the latest topics and a trend within OSC. As recommended by multiple scholars (e.g., Yuan, 2017), a ten year period is generally a typical time range for selecting the more recent articles for literature review; secondly, journal articles in the OSC domain started coming into the academic attention since 2008 (Fig.2), before which articles were not published in large quantities. It also makes more sense to observe the trend of annual article number since 2008. That is: the annual number was relatively stable from 2008 to 2010, and then significantly increased since 2011 until 2015, and another significant increase in 2016.

Peer reviewed and non-peer reviewed conference papers were excluded. Multiple studies (e.g., Butler and Visser, 2006; Yi and Chan, 2013) have explained the rationale for excluding conference papers but journal articles only (especially high-impact journals) for review-focused studies. Basically, the exclusion of conferences papers is based on the fact that conference papers are published in large amounts, but with less rich information compared to peer-reviewed journal papers. Excluding conference papers but only recruiting journal articles is a commonly accepted approach to conducting literature review, such as work undertaken by Oraee et al. (2017), He et al. (2017), Zhao et al. (2017) and Hosseini et al. (2018).

According to Fig.1, further refinements of collated literature were performed to screen out articles that did not fall into the scope of civil engineering, building construction, architectural engineering, and architecture. Articles within the intended scope, but not focusing on particularly on OSC were also excluded in the literature sample.

3.2.Scientometric analysis

The text-mining tool,*VOSViewer* (van Eck and Waltman, 2010), was applied to generate the visualized map in OSC. Besides VOSviewer, other text-mining tools used in other studies includes CiteSpace(Chen, 2016) and Gephi (Bastian et al., 2009). Compared to other text-mining tools,*VOSViewer* is suitable for visualizing larger networks and it also has special text mining features (Van Eck and Waltman, 2014). An increasing adoption of VOSViewercan be seen in assisting the literature review in the field of construction engineering and project management, such as public-private-partnership (Song et al., 2016), BIM (He et al., 2017), and building control (Park and Nagy 2018). It can also be applied in other potential research domains (Zhao, 2017).*VOSViewer* creates distance-based maps of networks where the distances among nodes indicate the level of closeness amongst them (Oraee et al., 2017). The data downloaded from certain literature sources (e.g., *Scopus*) can be transported into *VOSViewer* to generate the network among publications. Citation is one of the main measurements to quantify the influence of a scholarly work or a publication. According to van Eck and Waltman (2014), the use of direct citation has become a common measure to identify the most influential studies in a field. More detailed descriptions of working mechanism of *VOSViewer* can be found in Eck and Waltman (2014). Applying *VOSViewer* in scientometric review has been found in a few existing studies (e.g., Song et al., 2016; He et al., 2017) within the discipline of construction and project management, and potential other areas too (Zhao, 2017).

As recommended by Park and Nagy (2018), *VOSViewer* was adopted to: 1) import the literature source from *Scopus*; 2)visualize and compute the influence of key journals, scholars, publications, and countries in the research community of-site construction; and 3) analyze the co-occurrence of research keywords.Five categories within scientometric analysis was targeted besides an overview of the literature sample, including: 1) journal sources; 2) co-occurrence of keywords, 3) co-authorship analysis, 4) citation of articles, and 5) countries active in OSC research. These five categories were adopted as the core sections under scientometric analysis as they have been the most commonly adopted key contents in literature-reviewed based studies, such as in Song et al. (2016), Oraee et al. (2017), He et al. (2017), Zhao et al. (2017), and Hosseini et al. (2018). These categories provide a good overall view of the ongoing research in the selected domain. For example, the network of keywords indicates the frequently studied topics and their inter-relatedness. Secondly, these categories can facilitate the qualitative discussions and to help with addressing the four research questions. For example, the category of "countries active in OSC research" would show a list of countries in which more studies in evaluating the performance of OSC projects have been adopted. This would then lead to the discussion relating to the country background that would affect the performance of OSCprojects compared to traditional construction.

3.3.Qualitative discussion

Following the bibliometric analysis and science mapping, a qualitative discussion was conducted to evaluate the current research focus areas in OSC, to summarize the performance of OSC in comparison with traditional construction, to explore the gaps of integrating OSC to multiple other emerging construction concepts (e.g., BIM), and to provide recommendations for near-future research in OSC. Current main research areas within OSC were summarized, such as cost-benefit analysis (Hong et al., 2018) within OSC. Some inter-linked research themes were discussed based on existing findings, such as BIM and OSC, as well as integrated project delivery (IPD) and OSC. A framework illustrating the needs of OSC-related cross-disciplinary research was ultimately initiated.

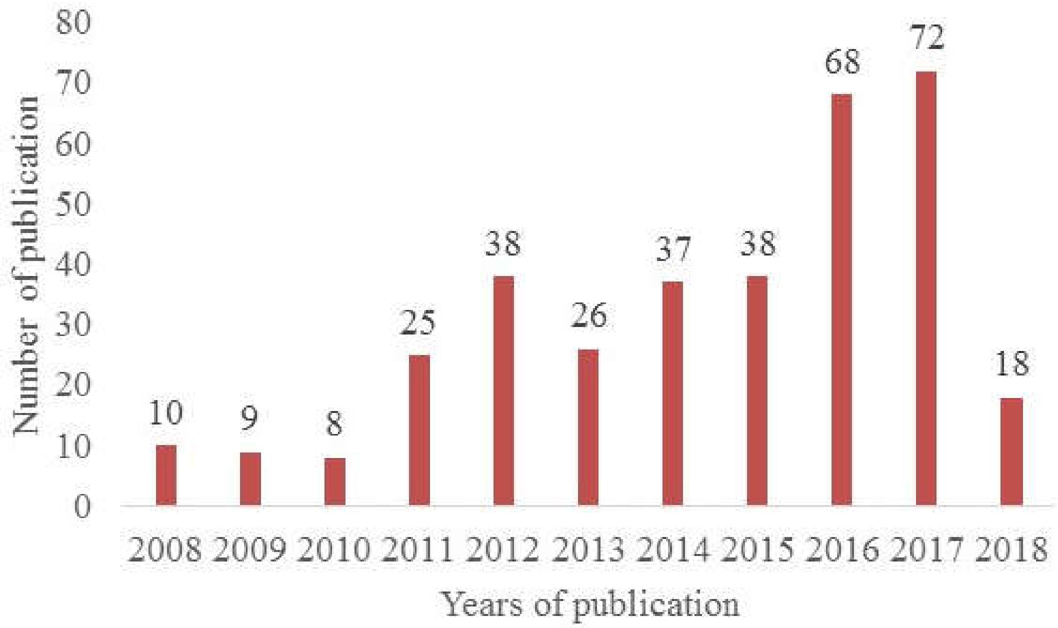
4. Results of Science Mapping

By performing the bibliometric search using pre-defined OSC keywords in Scopus, a total of *1,212* journal articles published from 2008 to 2018 were found, up to mid-February

2018. Pitfalls were found when researchers reviewed these initially-found articles.Keywords such as *modular construction*used in some articles could be semantically different in other fields, for example, computer programming (ParreiraJúnior and Penteado, 2018), chemistry (Fan et al., 2017), and biomedical material science (Medishettyet al., 2017). Even the keyword *prefabricated construction* could be ambiguous, as it might have different meanings in a different field (de la Sota et al., 2017). Therefore, a second round of screening was conducted to exclude articles with keywords in different semantic meanings. Upon completing the second-round screening, 857 articles remained with the correct semantic meaning of OSC which must contain one of these key keywords (i.e. modular construction) in their title, abstract, or keyword list. The third round of screening was performed to remove articles that has no focus on OSC. This was conducted even for the articles that belonged to the scope of architecture, civil engineering or relevant fields. For example, in the study of Jinet al. (2017), although prefabricated construction was mentioned in its linkage to BIM, the actual focus of the study was on BIM adoption. Therefore, articles similar to Jin et al. (2017) were also excluded. Finally, a total of *349* journal articles were recruited for the follow-up scientometric analysis. Following the summary of the yearly number of publications, the scientometric analysis covered the science mapping of journal sources, research keywords in OSC, active scholars, influential publications, as well as research-active countries.

4.1.An overview of the literature sample

Yearly journal articles published from 2008 to 2018 in the selected literature sample are displayed in Fig.2.



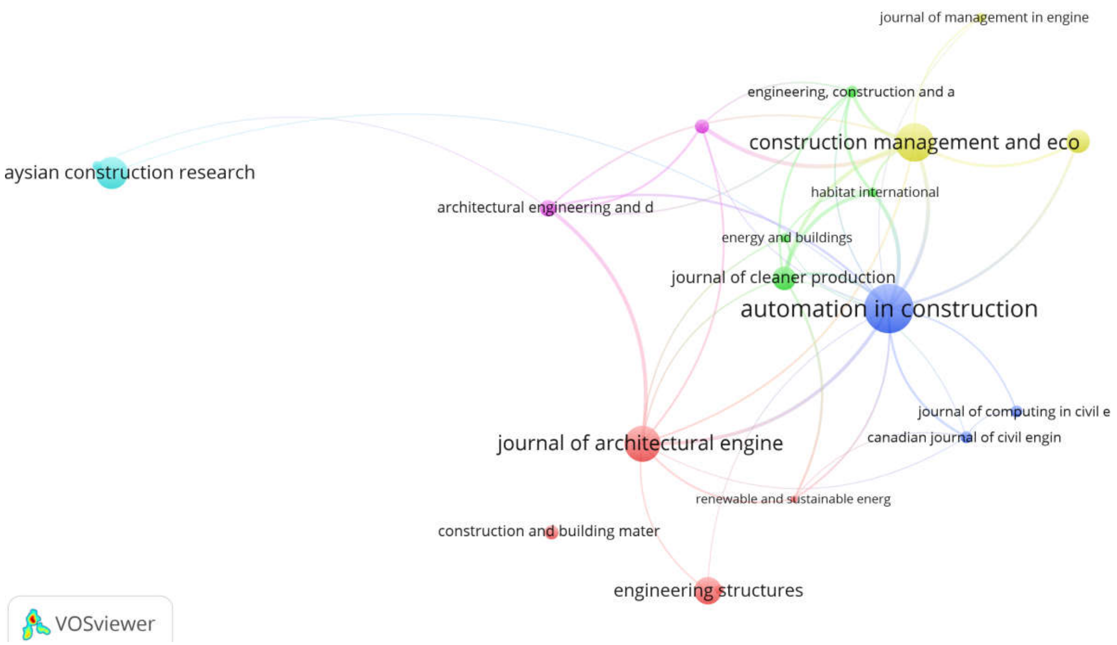
*Note: the number of journal papers in 2018 is incomplete as the articles selected in 2018 was up to the mid-February of 2018.

Fig.2. Yearly publications from 2008 to 2018

Fig.2 highlights the general increasing trend of publications from 2008 to 2017. The past ten years can be further divided into three periods: 1) 2008 to 2010 when the publication of OSC remained relatively low with yearly journal articles published not over *10* in *Scopus*; 2) 2011 to 2015 when the publication had been significantly increased to range from *25* to *38* annually; and 3) since 2016 the yearly academic publication has been skyrocketing to 68 or more. Therefore, with this current trend, it is expected that the research outputs in OSC would continue growing in the subsequent years.

4.2.*Science mapping of journal sources*

Sources of these OSC-related journal papers were identified using *VOSViewer*. Fig.3 displays the clusters and inter-relations among these journals.



*Note: Journal names may not be fully presented in*VOSViewer*. The full name of journals can be found in Table 1.

Fig.3. Mapping of influential journals in the research of prefabricated construction

Researchers set a minimum number of articles and a minimum citations of a source to be *3* and *20* respectively in *VOSViewer*. These threshold values regarding minimum number of documents and citations were selected based on two main reasons. Firstly, although there was no standardized way to set up the threshold value, these values were commonly adopted in other existing studies using Science Mapping, including Oraeeet el. (2017) and Hosseini et al. (2018). Secondly, multiple attempts were made with different threshold values in the text-mining tool, and it was found that these values were the most suitable ones to set the ideal range of sources. For example, around 20 most productive journals were filtered out of 138 sourcesin this case. The same two reasons applied when selecting threshold values in all otherinformation categories (e.g., keyword) of science mapping. As a result, a total of *19* out of *138* sources met the thresholds. Larger font and node sizes in Fig.3 indicate cases where relatively more articles were published from the given source. The connection lines indicate the mutual citation between given sources. For example, it can be found in Fig.3 that

Automation in Construction has a strong connection with *Journal of Computing in Civil Engineering* and *Canadian Journal of Civil Engineering* in the domain of OSC. Various colors assigned to journals in Fig.3 represent different clusters of sources. Thus, these journals were categorized into the same cluster: *Journal of Cleaner Production, Energy and Buildings, Habitat International,* as well as *Engineering, Construction, and Architectural Management*. These journals belonging to the same cluster tend to have a higher degree of inter-relatedness, meaning that there are higher frequencies that publications from these journals cite each other. The cluster visualization in Fig.3 also shows that some other journals (e.g., *Malaysia Construction Research*) seemed more isolated with the rest of journals publishing research outcomes in OSC. Detailed quantitative analysis of journals in terms of number of articles published, total link strength and citations are presented in Table 1.

Table 1. Analysis of sources (i.e., journals) publishing OSC research

Source	**Total link strength[1]**	**Number of articles**	**Total citations**	**Average citations**	**Ave. Norm. Citation[2]**
Architectural Engineering and Design Management	22	7	33	5	3.36
Automation in Construction	53	22	277	13	2.28
Canadian Journal of Civil Engineering	8	5	22	4	0.47
Construction and Building Materials	1	6	66	11	1.06
Construction Innovation	20	6	54	9	1.28
Construction Management and Economics	51	17	221	13	1.25
Energy and Buildings	9	4	100	25	3.00
Engineering Structures	4	12	51	4	1.36
Engineering, Construction and Architectural Management	26	5	67	13	1.23
Habitat International	32	4	79	20	2.83
Journal of Architectural Engineering	36	16	209	13	1.24
Journal of Cleaner Production	36	10	95	10	2.42
Journal of Computing In Civil Engineering	4	5	25	5	1.56
Journal of Construction Engineering And Management	11	10	55	6	1.09
Journal of Constructional Steel Research	3	4	22	6	0.66
Journal of Engineering Science And Technology	7	4	43	11	1.24
Journal of Management in Engineering	4	4	68	17	2.11

Malaysian Construction Research Journal	9	14	58	4	0.45
Renewable and Sustainable Energy Reviews	14	3	53	18	2.87

[1] Total link strength corresponds to Fig.3 and indicates the interrelatedness between the given journal and other peer journals.
[2] The Ave. Norm. Citation represents the normalized number of citations of a journal, document, author, or an organization. It equals the total number of citations divided by the average number of citations published in the same year. The normalization corrects the misinterpretation that older documents have more time to receive citations than more recent one (van Eck and Waltman, 2017).

The total link strength, number of articles, and total citations are generally highly correlated to each other, meaning that the productivity of research outputs of a given journal can be evaluated by either one of the three measurements. The average citation per document and the average normalized citation arewithout significant correlational relationship with other three measurements. Therefore, it isindicated that the significance of a journal contributing to the research community of OSC is not necessarily related to its number of publications. As highlighted in Table 1, the top-ranked journals in terms of their total number of publications and total citations include: *Automation in Construction, Construction Management and Economics,* and*Journal of Architectural Engineering*. However, in terms of the influence per publication, journals receiving the highest average citation per article include: *Energy and Buildings,Habitat International,Renewable and Sustainable Energy Reviews*, and *Journal of Management in Engineering*. The average normalized citation shows that these journal also have the high average influence per year, indicating their current and continuous influence in the OSC domain. Besides these journals, Architectural Engineering and Design Management, although not with the highest total or average citation, has shown its higher potential influence according to its current published articles which have received high annual citations.

4.3.Co-occurrence of keywords

Keywords represent the key contents of existing research and depict the areas studied within the boundaries of a given domain (Su and Lee, 2010). A network of keywords shows the knowledge in terms of relationships, patterns, and intellectual organization of research themes (van Eck and Waltman, 2014). Among the 349 articles finalized from the bibliometric search, “Author Keywords” and “Fractional Counting” were set in the text mining tool, as recommended by van Eck and Waltman (2014), Oraee et al. (2017) and Hosseini et al. (2018). In the initial output, initially *82* out of *1,129* keywords met the threshold. The inclusion and exclusion of keywords include a few main criteria: (1) the threshold value at a minimum of 3; (2) the general keywords such as “OSC”, “modular construction”, and “prefabricated construction”, “building”, “construction” to be removed; and (3) other keywords with semantically consistent meaning were combined, for example, BIM and “Building Information Modelling”. Finally, a total of 33 main keywords were shortlisted and visualised in Fig.4.

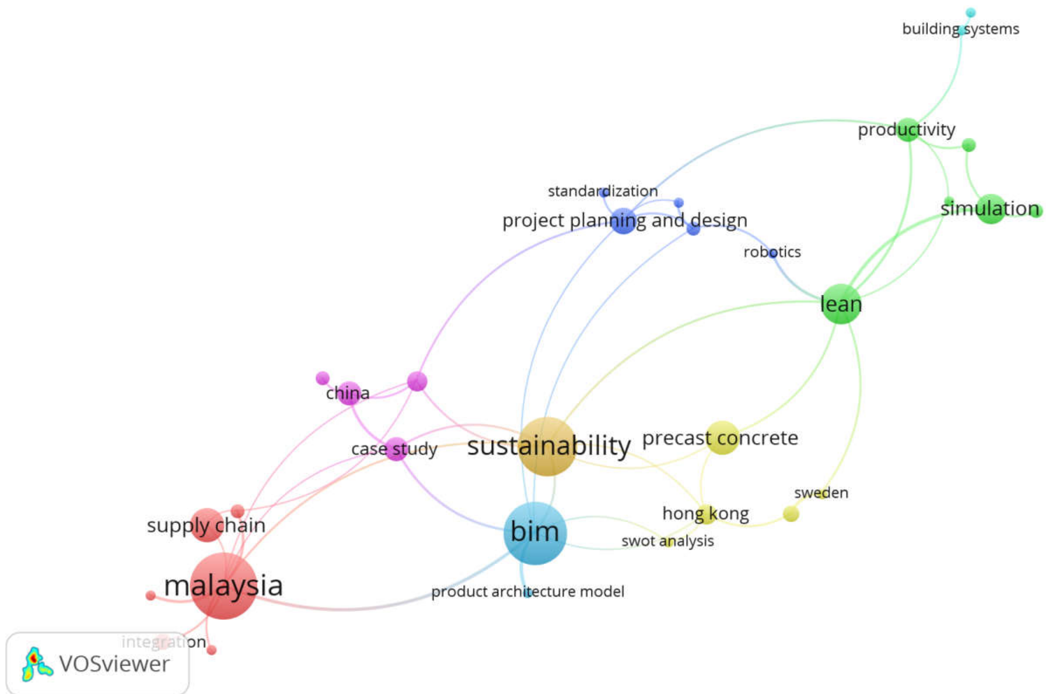


Fig.4. Co-occurrence of keywords in the research of OSC

It can be found from Fig.4 that sustainability was the most frequently mentioned research keyword. Other keywords that most frequently recur with sustainability include lean, BIM, case study, precast concrete, project planning and design, and Hong Kong. The main categories of keywords were derived based on the text mining of the frequently studied keywords from the literature sample. According to the text mining process and visualization of screened keywords shown in Fig.4, these categories were defined following the group discussion among the researchers in this study. Each keyword was assigned to a defined category. For example, sustainability fell into the category of performance. Details of these defined categories are explained below:

1) Management practices: OSC has often being linked to lean construction (Arashpour et al., 2016), which stay in the same cluster with productivity (Chen et al., 2017), simulation (Mitterhofer et al., 2017), and risk management (Shahtaheri et al., 2017);

2) Process: OSC does not simply refer to the assembly of building components at site, but involves early stages such as project design and planning (Choi et al., 2016), and production (i.e. automation (Isaac et al., 2016) and standardization (Lei et al., 2015));

3) Product: precast concrete is one of the commonly studied off-site manufacturing products;

4) Performance: OSC has been widely explored of its impact on sustainability (Kamali and Hewage 2016), and supply chain management issues (Wikberg et al., 2014);

5) Research method: case study (Gledson 2016, Wang et al., 2016) seems to be one popular research method in investigating CSFs in OSC;

6) Place: countries or regions where have been active in researching OSC, includes Malaysia, Hong Kong, China, and Sweden;

7) Technology: BIM has been extended to establishing the product architecture model (Ramaji et al., 2017).

Further studies such as observing the interconnections among BIM, lean construction, and sustainability reveal that existing studies (Nahmens and Ikuma, 2012; Lee and Kim, 2017) have established certain connections between BIM and sustainability, as well as between sustainability and lean construction. However, existing studies failed to utilize BIM in being applied in lean construction for OSC projects. Quantitative measurements of keywords are further summarized in Table 2.

Table 2. Summaries of Most Frequently Studied Keywords in OSC

Keywords Within OSC	**Total Link Strength**	**Occurrence**	**Average Year Published**	**Average Citations**	**Ave. Norm. Citation**
Adaptability	1	3	2013	4	0.34
Automation	4	4	2015	6	0.87
BIM	10	19	2016	4	1.22
Building systems	2	3	2013	9	0.98
Case study	5	7	2015	5	0.79
China	4	7	2015	14	2.03
Configuration	1	3	2013	8	0.76
Contractors	3	4	2013	5	0.52
Conventional construction	1	4	2015	23	3.21
Critical success factors	4	6	2015	6	0.82
HongKong	3	6	2013	27	2.07
Innovation	3	5	2011	35	1.97
Integration	1	5	2014	7	0.71
Lean	10	12	2013	14	1.57
Malaysia	11	20	2014	4	0.55
Mobile crane	2	3	2014	7	0.82
Optimization	2	4	2017	0	0.33
Precast concrete	2	10	2014	6	1.01
Product architecture model	3	3	2017	3	1.13
Productivity	5	7	2014	8	1.12
Project planning and design	5	8	2015	6	0.92
Readiness	2	3	2015	0	0.06
Risk management	1	4	2012	9	1.44
Robotics	3	3	2012	5	0.32
Safety	2	3	2013	4	0.66
Simulation	6	9	2014	8	1.24
Standardization	1	3	2015	6	1.17
Supply chain	1	10	2015	2	0.43
Sustainability	7	18	2014	7	1.23
Sweden	3	3	2013	13	1.31
Swot analysis	1	3	2015	3	0.78
Transportation	1	3	2015	3	1.49

The total link strength shows the connections between the given keyword and the rest keywords according to the text mining within the literature. In this study, BIM, lean, and Malaysia were found with highest degree of inter-relatedness with other keywords. According to occurrence (i.e., frequency of keywords appearing in the literature sample), most widely studied keywords in OSC include BIM, sustainability, followed by lean construction, precast concrete, and supply chain management. Multiple studies (Kamar et al., 2014; Nawi et al., 2014; Ismail et al., 2016) focused on the movement of OSC in Malaysia, addressing various issues such as sustainable and carbon footprint (Zaini et al., 2016), fragmentation problem in the project delivery process (Nawi et al., 2014), and CSFs in adopting IBS (Kamar et al., 2014). The average publication year indicates the recentness of these keywords. According to Table 2, BIM, product architecture model, and optimization seem to be emerging keywords in OSC. Optimization could refer to different attributes within off-site practice, for example, material usage through life cycle with technical modularity (Ji et al., 2013), and energy efficiency in modular construction (Xie et al., 2018). The approach to achieve optimization may include RFID (i.e., radio frequency identification) and generic algorithm in design (Altaf et al., 2018). In comparison, keywords including innovation, risk management, and robotics have been studied in earlier years, with their average publication years mainly 2011 and 2012.

Average citation and average normalized citation listed in Table 2 indicate the influence of the keyword in the research community. These keywords, including innovation, Hong Kong, and conventional construction, received highest average citations, indicating that studies focusing on innovation, conducted in HK, and addressing the comparison between OSC and conventional method had received more attention in the academic community. Innovation generally means that off-site manufacturing, as a new construction technique, causes changes of design, working platform or project workflow (Onyeizu and Bakar, 2011;

Thuesen and Hvam, 2011), requiring decision-making and evaluation from stakeholders at both individual and organizational levels (Alshawi et al., 2012; Hedgren and Stehn, 2014). Uncertainties and risks were associated with the new approach, such as cost, health, and safety (Pan et al., 2008).

4.4. Co-authorship analysis

Knowledge of the existing collaborations in a research field enhances the access to funds and expertise, improves productivity, and prevents researchers from isolation (Hosseini et al., 2018). In this study, the minimum number of publications and the minimum number of citations were set at *3* and *20* respectively in *VOSViewer* to filter authors that met the threshold. As a result, *38* out of a total *888* authors were identified from the co-authorship analysis. Fig.5 displays the main research collaborations among these most productive authors who have also been actively involved in collaborative research in the OSC domain.

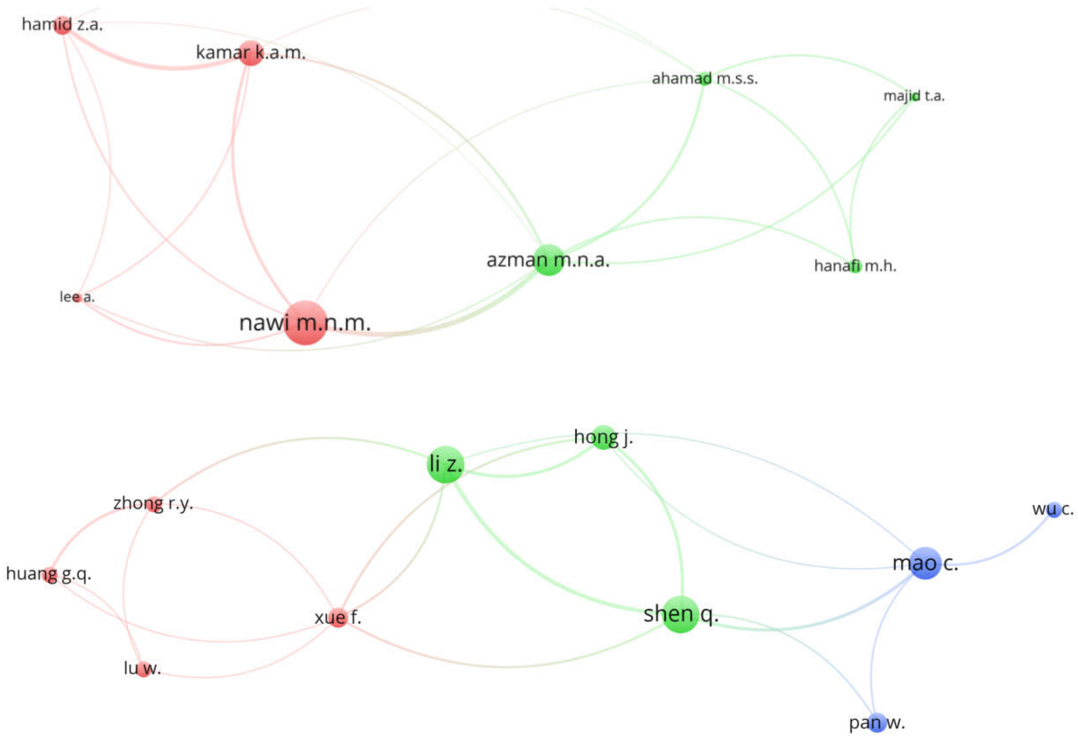


Fig.5. Co-authorship analysis

It can be seen in Fig.5 that some authors and clusters have been more productive and more collaborative in recent years, including the cluster of NawiN.N.M., Kamar, K.A.M., and Hamid, Z.A., the group consisting of Hong J., Li C.Z., Shen G.Q., and Li Z., the research cluster of Mao C., Pan W., and Wu C., as well as the collaboration among Azman, M.N.A, Ahamad M.S.S., Hanafi, M.H., and Majod, T.A. Viewing these collaboration networks could further unveil the main research topics that have been targeted within each network group. For example, the research network group consisting of Hong J., Li C.Z., Shen G.Q., and Li Z. have been highly focusing on OSC project performance (e.g., Hong et al., 2016; Hong et al., 2018). Furthermore, the research network indicates that the OSC research could be cross-institutional or under international collaboration. It could lead to further investigation of countries active in OSC research and whether the OSC research topics were specific to certain countries' context.A quantitative summary of these productive authors is provided in Table 3.

Table 3. List of active scholars in OSC research

Author	**Number of articles**	**Authors' contribution score**	**Total citations**	**Average publication year**	**Average citation**	**Avg. Norm. Citation**
Hong J.	5	1.35	43	2017	9	2.53
Li Z.	8	2.49	84	2017	11	2.18
Lu W.	3	1.23	56	2014	19	6.52
Mao C.	7	2.20	106	2016	15	2.56
Pan W.	4	1.85	124	2012	31	2.69
Shen Q.	8	1.72	157	2016	20	3.16
Zhong R.Y.	3	0.96	13	2016	4	5.29
Wu C.	3	0.44	35	2016	12	1.79
Xue F.	4	0.70	34	2017	9	5.55
Ahamad M.S.S.	6	1.24	34	2012	6	0.54
AzmanM.N.A.	14	4.00	73	2014	5	0.59
Hamid Z.A.	8	1.8	65	2012	8	0.90
Hanafi M.H.	6	1.09	32	2013	5	0.51
KamarK.A.M.	11	2.71	111	2013	10	1.11
Lee A.	4	0.96	61	2014	15	1.68
Majid T.A.	4	0.99	32	2011	8	0.77
NawiM.N.M.	20	5.66	92	2015	5	0.59

Author's Contribution Score is a measurement of individual author's contribution to an article. It is based on Formula (1) proposed by Howard et al. (1987):

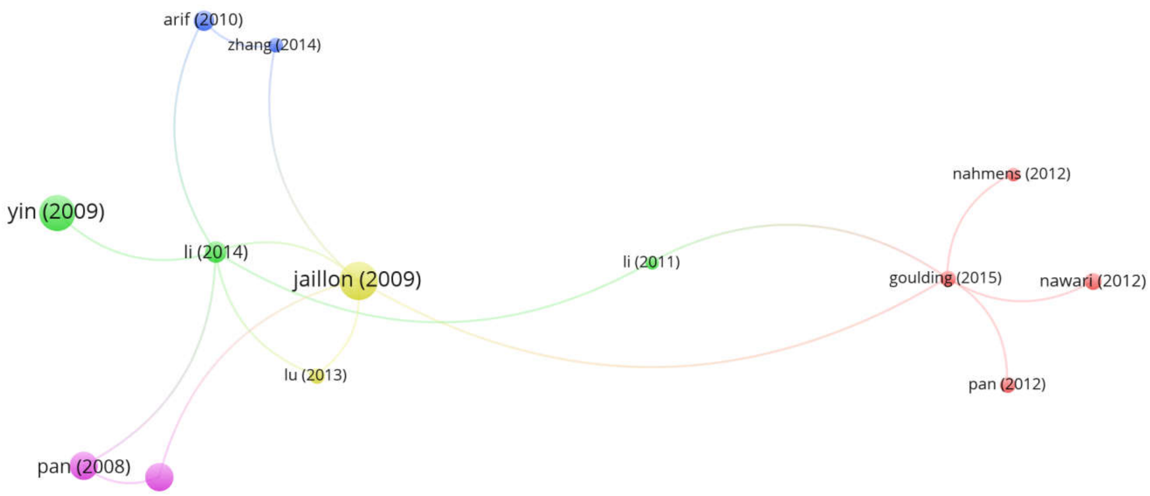
$$Score\ in\ a\ indiviudal\ paper = \frac{1.5^{n-i}}{\sum_{i=1}^{n} 1.5^{n-i}} (1)$$

where$n$ is the author number in the same paper, and i denotes the author's ranking in the paper. By summing up the scores of all articles for the same author, the Authors' contribution score is obtained and listed in Table 3.

A total of *17* productive authors are listed in Table 3. According to Author's Contribution Score, these scholars, including AzmanM.N.A., Li Z., and Mao C., have been productive in contributing to OSC research. The number of publications and citation-related items are other measurements of an author's contribution to OSC research. The number of publications and total citations were found not significantly correlated to each other, with the Pearson correlation at *0.452* and the corresponding p value at *0.069*. The correlation analysis indicated that an author's number of publication is not the same with his or her contribution to the research field of OSC which is measured by total citations and the average citation per publication. According to Table 3, the most productive authors in the recent decade are NawiM.N.M., AzmanM.N.A., and KamarK.A.M. But in terms of overall research significance, these authors top Table 3: Pan W., Mao C., and KamarK.A.M. In terms of the significance per research article, the top-ranked authors also slightly differ: Pan W., Lu W., Lee A., and Mao C. When it comes to average normalized citation, Lu W., ZhongR.Y., and Xue F. topped the table. The latter two authors, though relatively new in the OSC domain and not with the highest average citation, have had one of the highest average citation of their publication per year, indicating their potential influence in OSC. Some scholars listed in Table 3 had established their research profile in OSC in earlier years, such as MajodT.A., whose average year of publication was 2011. More recently, these emerging scholars (including Hong J., Li C.Z., and Xue, F) have made their contributions to the research community..

4.5.Citation of articles

Researchers also aimed to identify publications with highest impact in the research community. Setting the minimum citation at *30;13* out of a total number of *349* articles met the requirement. Fig.6 displays these articles with the highest citations and strong links to other articles.



*Note: only the first author of each article is displayed in *VOSViewer*, more details of each article can be found in Table 5.

Fig.6. Science mapping of OSC publications

The influence of these articles measured by their number of links and total citations are summarized in Table 4.

Table 4. List of publications with highest impact in OSC

Article	Title	Number of links	Number of citations	Norm. citations
Goulding et al. (2015)	New offsite production and business models in construction: priorities for the future research agenda	5	29	5.30
Li et al. (2014)	Critical review of the research on the management of prefabricated construction	6	41	4.76
Zhang et al. (2014)	Exploring the challenges to industrialized residential building in China	2	26	3.02
Lu and Yuan (2013)	Investigating waste reduction potential in the upstream processes of offshore prefabrication	2	28	2.33

	construction			
Mao et al. (2013)	Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects	2	55	4.57
Pan and Goodier (2012)	House-Building Business Models and OSC Take-Up	1	29	2.76
Nawari (2012)	BIM Standard in OSC	1	32	3.04
Nahmens and Ikuma (2012)	Effects of Lean Construction on Sustainability of Modular Homebuilding	1	25	2.38
Li et al. (2011)	Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong	2	25	2.85
Arif and Egbu (2010)	Making a case for offsite construction in China	2	39	2.69
Yin et al. (2009)	Developing a precast production management system using RFID technology	1	74	3.11
Jaillon and Poon (2009)	The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector	5	79	3.32
Pan et al. (2008)	Leading UK housebuilders' utilization of offsite construction methods	2	56	2.31

The number of links listed in Table 4 shows the influence of the article within the research community. Two review-based articles (i.e., Li et al., 2014; Jaillon and Poon, 2009) have the strongest link and highest number of citation respectively. Li et al. (2014) reviewed the research from construction management related journals and summarized the main research topics within management of prefabricated construction, namely "industry prospect", "development and application", "performance evaluation", "environment for technology application", and "design, production, transportation and assembly strategies". These main topics are consistent with keywords visualized in Fig.4, such as transportation, and performance in terms of sustainability. Keywords related to industry practice, development, design, production, and technology application were also highlighted in Goulding et al. (2015), who investigated the indicators and directions of OSC. As one of the technological applications, RFID was emphasized by Li et al. (2014) in its effectiveness of being adopted in improving the performance of OSC. Corresponding to Li et al. (2014), RFID applied in OSC in the study of Yin et al. (2009) received one of the highest citations. The study of Jaillon and

Poon (2009) received the highest citation and one of the highest link strength. It reviewed the movement of prefabricated construction in HK's public and private housing industry. This study used the database of *179* prefabricated buildings and five case studies to generate the overall picture of prefabrication percentages by volume and types of precast elements. Other publications receiving higher citations focused on comparison between OSC and conventional approach (Mao et al., 2013), usually with case studies adopted in the context of a certain country (Pan et al., 2008; Arif and Egbu, 2010).

4.6.Countries active in OSC research

Fig.4 and Table 4 both indicated that OSC studies were commonly performed within the context of a certain country or region. Countries were also explored of their contributions to the research field of OSC. The minimum number of publications and citations were input as *3* and *20* respectively in *VOSViewer*, resulting in *18* out of totally *42* countries being selected. Fig.7 visualizes these research-active countries in prefabricated construction.

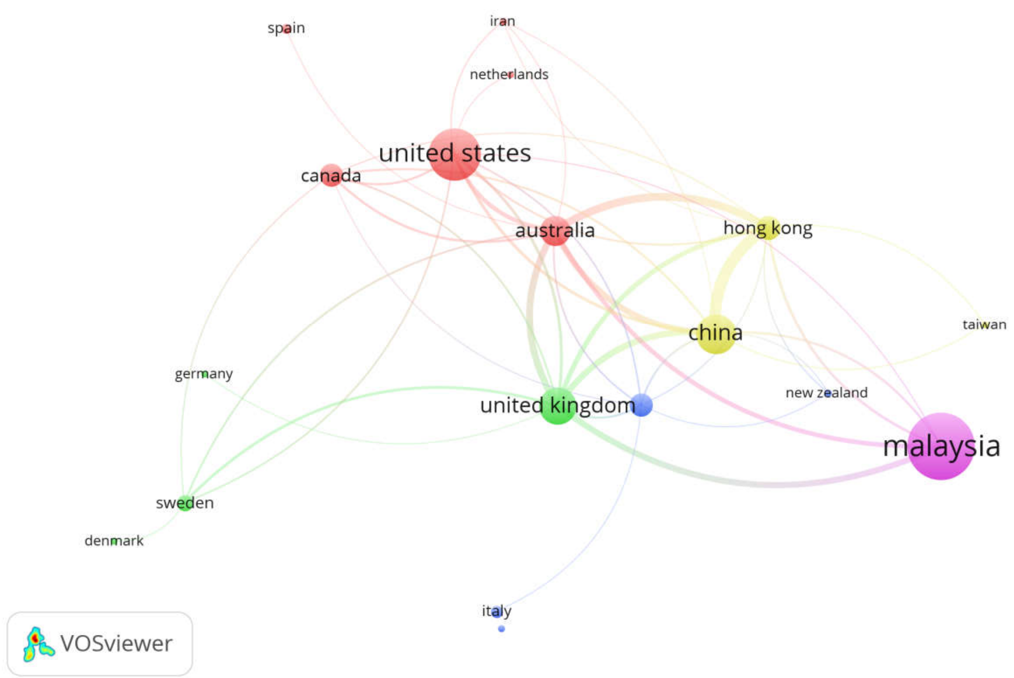


Fig.7. Mapping of countries where OSC researchers were located

It can be seen in Fig.7 that scholars from geographically close countries are more likely to have mutual influence, or more likely to cite each other's work, for example, scholars from mainland China, Taiwan, and HK in the Asian context, those from UK, Germany, Sweden, and Denmark in the European context, as well as the cluster of U.S. and Canada from North America. Both developed and developing countries have been active in the research of OSC, such as U.S. and Malaysia respectively. Although Malaysia stands high in publication number, it forms its only cluster without adequate inter-correlations with other countries (see Fig.7). The quantitative measurements of countries are provided in Table 6.

Table 6. Countries where OSCresearchers are based

Country	**Total link strength**	**Number of articles**	**Number of citations**	**Average publication year**	**Average citation**	**Ave. Norm. Citations**
Australia	182	32	203	2016	6	1.71
Canada	42	23	184	2015	8	1.76
China	187	43	352	2016	8	1.86
Denmark	2	5	24	2013	5	0.52
Germany	5	5	21	2016	4	0.92
Hong Kong	181	25	382	2015	15	2.65
Iran	12	6	21	2015	4	2.08
Italy	6	11	54	2015	5	1.00
Malaysia	76	79	326	2014	4	0.61
Netherlands	7	5	67	2013	13	1.23
New Zealand	11	5	27	2015	5	3.60
South Korea	34	23	55	2016	2	0.70
Spain	4	9	148	2012	16	1.03
Sweden	31	15	183	2014	12	1.16
Taiwan	10	6	90	2014	15	1.03
Turkey	2	6	25	2012	4	0.65
United Kingdom	168	40	433	2013	11	1.27
United States	76	59	449	2014	8	0.95

*Note: not all 32 countries are listed in Table 6 but the top 20 countries with most OSC articles published

U.S. and Malaysia are ranked higher in Table 6 in terms of the number of publications. Among these countries active in OSC research, scholars from the U.S. received the highest total citations. In terms of influence and mutual citations, these countries or regions (i.e., Australia, China, HK, and UK) have been playing an active role in moving forward the research direction of OSC. The average citation, differing from other quantitative measurement indicates the significance of the research performed in the country or region. For instance, countries and regions including but not limited to HK, Netherlands, Spain, Sweden, and Taiwan where important research outputs are generated. Countries or regions including Australia, Canada, mainland China, HK, Iran, and New Zealand, with the higher average normalized citation, have shown their current position in, and influence of OSC research.

5. Qualitative Discussions

Following the scientometric analysis of journals, scholars, publications, and countries involved in the research community of OSC, a qualitative analysis was carried out to highlight our findings in the following four approaches: 1) to summarize the main research topics; 2) to analyse the performance of OSC; 3) to discuss the potential integration of OSC with other emerging construction concepts (e.g., BIM); and finally 4) to provide recommendations for future research. All these discussions directly reflect on the earlier research questions and the science mapping studies conducted as part of this research study. As shown in the previous section, the categorization of research topics is primarily generated from the keyword analysis in the conducted science mapping(see Figure 4 and Table 2). By conducting this keyword analysis, the study provides a new set of findingsto identify key associated research areas to OSC. This pragmatic approach is supported in such research of keyword analysis in various research studies such as Song et al. (2016) and Zhao (2017). In this approach, the research areas are ultimately identified based on their occurrence in the literature, which is also benefitted from a weighting analysis that not only suggests a range of research studies but also evaluates their strength in research (i.e. through occurrence and citation). For instance, 'sustainability' appeared as one of the main research areas in the literature and is also associated to many other research topicssuch as lean (Erdil et al., 2018) and BIM (Fitriaty and Shen, 2018). Since its influence, occurrence,and citation are significant in the literature, it is categorized as a major research topic as well as an associated topic to other research topics in OSC. Moreover, by linking back to earlier findings in the previous section, this section first highlights a variety of research topics within OSC and then provides an overview of performance measurement indicators of OSC and integration of OSC with other emerging construction concepts. Finally, this section provides proposed research directions of OSC, which are also summarised in Fig. 8.

5.1.Research topics within OSC

5.1.1. Prefabricated products

Precast concrete has been a mainstream OSC component in both academic research and practice. Reinforced-concrete was found as the predominant structure type in developing countries such as China (Ji et al., 2017). The academic community has been highly concerned on codes and standards adapted for the safe design and structural reliability (Cavaco et al., 2018). Emphasis has been given to comparison of structural and material performance between precast concrete members and the conventional on-site cast concrete, such as serviceability in terms of deflection and crack development (Park et al., 2017), joint connection analysis between precast concrete members (Sung, et al. 2017). The joint connection between precast members (Nzabonimpa et al., 2017, Raghavan and Thiagu, 2017) has been one of the main research topics in precast concrete. The joint which connects precast components is a key issue in applying the prefabrication system in construction projects. By comparing the IBS beam-to-column connections to the conventional reinforced concrete connection, Moghadasi et al. (2017) found that a new IBS system had certain advantages in terms of more rotational ductility. The structural behaviour under lateral loading of precast connections were found similar to that of traditional frames (Kothari et al., 2017). The wall-to-wall connection designed and tested by Vaghei et al. (2017) showed that the precast connection was capable of exceeding the energy absorption of precast walls and further improving the seismic resistance performance. These multiple studies all focus on the structural performance of precast concrete components and all display positive outcomes in comparison to the conventional approach. Much of this has focused on prefabricated products in construction and methods of optimising construction process, project management, and project costing. Also in a recent study on comparing greenhouse gas (GHG) emissions of precast approach and conventional methods, Ji et al. (2018) identified four positive contribution of precast methods, namely on (i) embodied GHG emissions of building materials, (ii) transportation of building materials, (iii) resource consumption of equipment and techniques and (iv) transportation of waste and soil. These identify the positive factors contributing to the optimisation of construction process. Moreover, the ongoing research and consultancy work in promoting the wider implementation of precast components would be towards establishing the design codes and standards.

5.1.2. Sustainability within technical studies of OSC

It is important to highlight the integrated research topics within the field of modular construction. For example, the structural performance analysis within precast component had been linked to sustainability of material reuse and recycle. Ng et al. (2016) applied the oil palm shell (OPS) as recycled coarse aggregates in precast floor panels and tested the panel performance. Although the early days' mechanical properties of precast panels containing OPS turned out disadvantageous, the work of Ng et al. (2016) could lead to more studies in optimizing sustainability and structural performance in precast building components. Sustainability within technical development of OSC products has been integrated with other key factors (e.g., cost) within decision making in prefabricated construction. For example, Bansal et al. (2017) evaluated the applicability of OSC for stakeholders by weighting the environmental sustainability with technical factors. By identifying sustainability factors. Abanda et al. (2017) suggested for contributions to maximization of efficiency and productivity of construction process; through which we can identify technical approaches for the better deployment of OSC in practice. Although there are many positive factors on sustainability matters of OSC implementation, there remain issues of potential increase of costing in prefabricated housing (Postnote, 2003) and over design processes before site delivery (Hairstans, 2010). Hence, there are still scope for improvement of OSC processes, and particularly in regard to the associated matters to sustainability. Furthermore, as a cleaner construction method (Li et al., 2016; Mao et al., 2016; Hwang et al., 2018), OSC provides a sustainable integrated platform in comparison to the conventional approach; through which management and technicality of the projects are optimized at the implementation phase.

5.1.3. Managerial and technical issues in OSC implementation

Among these CSFs to successful completion of OSC, a prominent study is the one on project delivery process conducted by Osman et al. (2015). Integrated project delivery (IPD) was proposed as an approach to overcome the fragmentation in traditional construction (Nawi et al., 2014). Theoretically, IPD could boost the supply chain management in OSC. Hence, the integration is essential between construction concepts such as IPD into OSC. More recent research is focused on the workflow from manufacturing in factory and transportation, to site assembly for OSC projects. Inefficient use of resources and delayed delivery have been an issue in prefabricated construction (Kong et al., 2017). Methods such as the application of simulations, computational algorithms and programming to optimise the production and delivery efficiency have been considered as effective approaches in research (Shewchuk and Guo, 2012; Arashpour et al., 2016; Kong et al., 2017; Mitterhofer et al., 2017). These studies emphasized the planning and scheduling to minimize changeover time and increase the project delivery speed. Hence the integrated methods are procedural methods of optimizing the overall managerial and technical factors of OSC implementation.

Furthermore, multiple managerial and technical factors (e.g., IPD, BIM, lean construction) could be utilized to enhance OSC practice (Grosskopf et al., 2017). For example, BIM could provide visualization and monitor the work progress between off-site and onsite activities in OSC project workflow (Salama et al., 2017). Lean production principles, when successfully implemented in OSC, resulted in nearly 50% increase in productivity and 25% reduction in lead time (Nahmens and Mullens, 2011). Similarly, Court et al. (2009) estimated a reduction of 35% on-site labor, and lowersite injury risks in lean OSC projects. In order to achieve the superior project performance, integration of multiple stakeholders and project parties in the design stage for OSC project is deemed a key factor (Othman et al., 2016). Many projects of such kind indicate the possibilities of integrated methods, through which we can argue in favor of optimization means and the use of information-based management systems in the whole construction process. To address the current gaps in OSC, there is a further need to study the mechanism of how IPD, BIM, and lean construction could be integrated into the design collaboration. This can be conducted by initiating the theoretical framework tested by case studies. Yet, such studies should highlight the multi-dimensional nature of practice and the methods in which integration was occurred or enabled for the purpose of OSC implementation. Hence, it is possible to use OSC to minimize the lifecycle cost (Mao et al., 2016) and to better develop a clearer framework for all parties in the construction process. In their meta-perspective analysis, Hosseini et al. (2018) concluded that the future work of OSC is about optimization of all processes at key levels of operational, management and strategic considerations. But more importantly, they highlighted the alignment of these processes with the current practice that includes a variety of aspects such as collaborations, communications, and etc. As a result, it is important to advocate for a comprehensive package of optimized processes from both managerial and technical attributes.

5.2.Performance measurement and indicators of OSC

A considerable amount of effort has been paid in exploring the differences between OSC and the conventional approach. Cost, time, and waste generation (Yarlagadd et al., 2017) have been widely adopted measurements for the performance of prefabricated construction. Empirical data from site investigations were collected from these studies. Chen et al (2017) adopted a comprehensive research approach from site observation, expert interview, and mathematical model to evaluate the performance throughout the planning, design, installation, and manufacturing for precast projects. It was found that precast projects could increase the corporate profits by nearly 40%. Environmental sustainability of prefabricated projects is another performance measurement. Kamali and Hewage (2016) stated that modular buildings had a better life cycle performance in terms of energy performance. The research in OSC performance has also been extended from cost and schedule to safety. Fard et al. (2017) suggested that safety programs and standards accommodate OSC.

Despite the potentially superior performance of OSC being documented in the empirical studies, the real project success depends on many factors. Choi et al. (2016) stated that not all executed modular projects have resulted in successful performance. Several scholarly work shed light on the CSFs to the cost and time performance of modular construction, such as design coordination, equipment specification, vendor involvement, technological advancement, and risk management in execution (Choi et al., 2016; Mitterhofer et al., 2017). A systematic approach performed by Goulding et al. (2014) indicated that the implementation of OSC should integrated human resources, process update, and technological drivers. The current studies of performance measurement and indicators still seem to be isolated as inferred by Hosseini et al. (2018), the integration of digital technology and sustainability (e.g., lean) in the OSC context is much needed. A closer linkage between performance measurement and performance indicators should be established, for example, the industry readiness (Osman et al., 2017) and the productivity (Jeong et al., 2017) in OSC projects. These studies focused on performance measurement and indicators and highlighted the overall optimised process of OSC in comparison to the conventional approach.

Overall, the weightings and decision criteria from stakeholders' perspective in OSC were found insufficient (Bansal et al., 2017). Multiple criteria could affect investors' decision in implementing OSC, including but not limited to its cost compared to conventional construction. Database, either a larger sample of prefabricated projects or detailed case studies (e.g., Jaillon and Poon; 2009; Hong et al., 2018) are needed to generate a more holistic picture of the performance of OSC. The performance of OSC needs to be placed in a certain country or region's context, as the research outcomes could vary among studies. For example, Pan and Sidwell (2011), Li et al. (2014), Gasparri et al. (2015), and Tam et al. (2015) believe that OSC was cost-effective, but Nadim and Goulding (2010), Zhai et al. (2014), and Mao et al. (2016) revealed different findings indicating that OSC led to higher cost due to multiple factors (e.g., incremental cost to adopt new prefabrication techniques). To analyze the benefits and barriers in cost changes caused by implementing prefabrication, Hong et al. (2018) initiated the cost-benefit analysis framework by comparing OSC and conventional method through different project stages (e.g., design). Adopting eight case studies in China, Hong et al. (2018) found that the cost intensity of prefabricated buildings was 26.3% to 72.1% higher than that of conventional houses. A more holistic performance evaluation covering environmental, social, technical, and aesthetic aspects beyond the cost performance was recommended by Bansal et al. (2017).

5.3.Integration of OSC with other emerging construction concepts

It should be noticed that OSC is not an isolated construction concept, but inherently connected with other emerging concepts such as BIM and lean (Eastman et al., 2011; Abanda et al., 2017). The inter-connected nature between OSC and other emerging concepts need to be understood before being integrated in practice.

5.3.1. Project delivery method

IPD has been proposed as an approach to enhance the multi-party collaboration throughout the fabrication, transportation, and construction of off-site projects (Osman et al., 2015). There are needs of further research on how IPD or other fast-track project delivery methods (e.g., Design-Build) could provide the systematic support to the successful implementation of OSC projects. Industry practitioners in OSC have complained about the failure of OSC to deliver the expected project performance. There have been limited studies regarding the mechanism of how IPD or other collaborative project delivery method could enhance the workflow involved in OSC from the life-cycle perspective. According to Fig.4, limited studies have addressed the inter-relatedness between project delivery method and OSC. Managerial barriers widely exist in applying IPD to OSC, such as unfamiliarity of workers to the practical innovations and technologies involved in OSC (Nahmens and Ikuma, 2012). The successful application of IPD or other innovative project delivery method in OSC would depend on project parties' collaboration, coordination, and effective communication. Currently, limited studies have showcased how an appropriate project delivery method has enhanced OSC project performance. Future studies could be performed to compare the effects of IPD in OSC and conventional site construction.

5.3.2. BIM, lean, sustainability, and DfMA

Identifying the inter-relatedness between BIM, lean construction, and sustainability with regard to OSC has been attempted (see Fig.4). Multiple existing studies have proposed strong links between BIM and OSC (Babič et al., 2010; Mann, 2017). The integration of BIM has not been achieved from the practical perspective (Goulding et al., 2015). Moreover, previous studies have failed to utilize the potentials provided by BIM to enhance sustainability, although BIM, lean, and sustainability are inherently inter-related concepts for being integrated (Eastman et al., 2011). BIM has been mostly applied in conventional construction, and has not been fully utilized to assist OSC (Abandaet al. 2017). From the sustainability perspective, there have not been sufficient studies addressing thermal comfort or indoor welling in prefabricated construction. Facility management for OSC projects could be further studied. Adaptability of prefabricated buildings according to season change and local climate, as indicated by Becerra-Santacruz and Lawrence (2016) requiresfurther investigation.

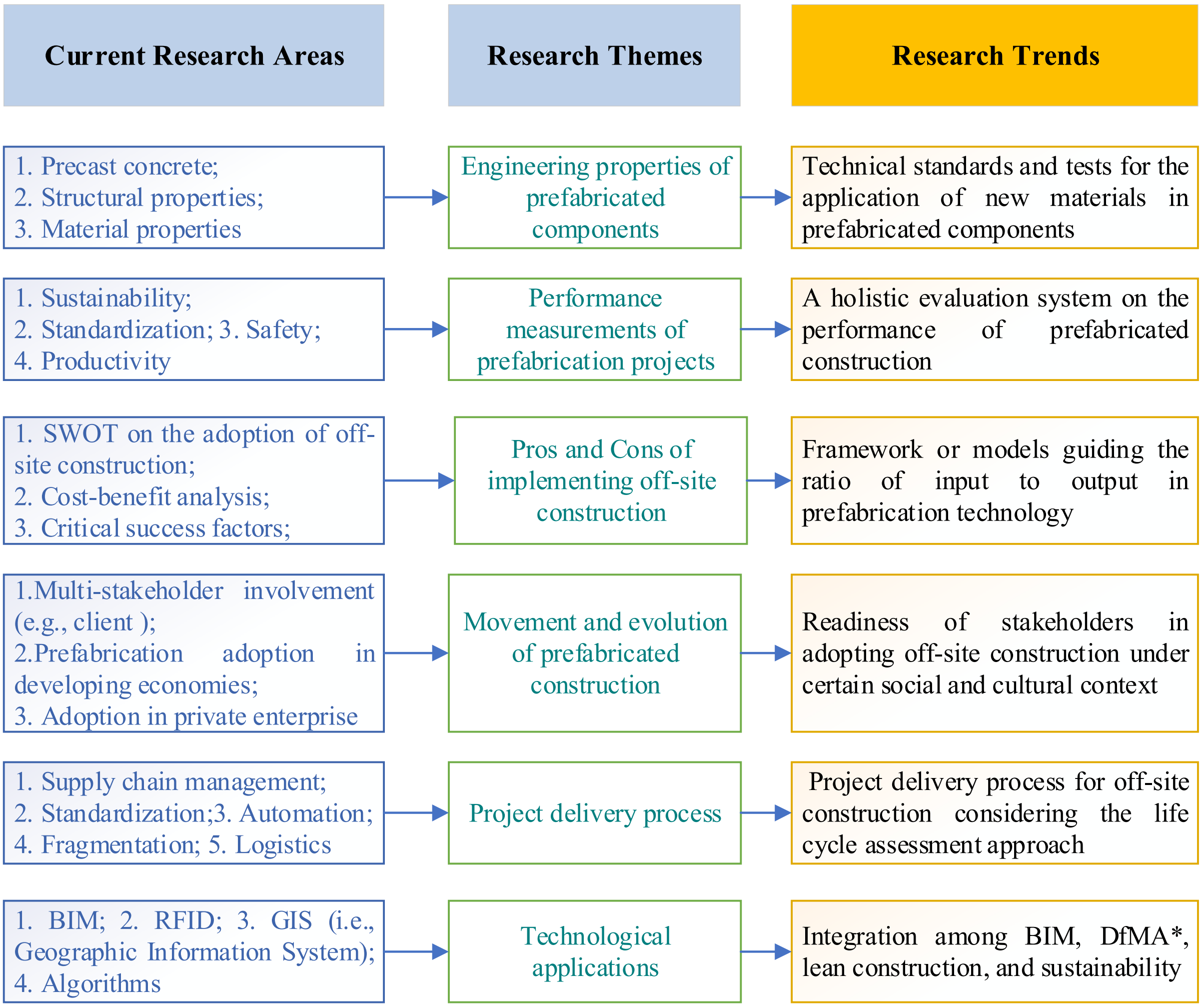
DfMA (i.e., Design for Manufacturing and Assembly), defined by RIBA (2013) as an approach that facilitates greater off-site manufacturing and minimizing onsite construction, is closely associated with prefabrication (Laing, 2013). RIBA (2013) noted that DfMA harnesses a wide spectrum of tools and technologies, including (1) volumetric approaches, (2) 'flat pack' solution, (3) prefabricated sub-assemblies. In Singapore, the DfMA concept was interpreted in a similar fashion. However, few studies have addressed the linkage between OSC and DfMA, in which it seems a main gap which is worth exploring.

The adoption of prefabricated components demands the adaptation of existing design standards and needs a better understanding of building performance, such as the tolerance in dimensional and geometric variation (Shahtaheri et al., 2017), thermal comfort (Becerra-Santacruz and Lawrence, 2016), energy performance (Jeong et al., 2016), and the structural and material properties (Raghavan and Thiagu, 2017). Further investigations are required to not just compare the cost between industrialized buildings and conventional construction, but also the technical properties to gain a more comprehensive evaluation.

It should be noticed that the integration of OSC with emerging concepts are not limited to BIM, lean, and DfMA, but could reach more state-of-the-art digital practice, such as RFID (Yin et al., 2009), GIS (Azman et al., 2012), and algorithm (Olearczyk et al., 2014). For example, GIS can be seen as a useful tool in locating OSC manufacturing plants (Azman et al., 2012). Algorithms can be applied in assessing the site operation activities for OSC projects (Olearczyk et al., 2014). These practices signify the integrational nature of the OSC in practice. Currently there have been insufficient integrations of these digital practices into OSC project delivery process from the practical perspective. Limited studied have been performed to investigate how these digital practices have affected the OSC project performance.

5.4.Proposed research directions for OSC

Based on the science mapping and qualitative analysis of current research areas within OSC, the framework that links the existing studies to future directions is initiated in Fig.8. In this diagram the three elements of ‘current research areas’, ‘research themes’, and ‘research trends’ are cross-linked. These are all put together to link current research areas in OSC to future research directions. In the first column of Fig. 8, current research areas are identified from the earlier conducted scientific mapping especially keyword analysis. These are then associated with a range of relevant research themes that are identified in this study. For example, sustainability is linked to a performance measurement of OSC projects. To emphasizethe research findings generated from the existing literature in the first two columns, the possibilities for future research directions are mapped accordingly. These are associated with the existing research themes that are explored in the earlier study (e.g., the integration of BIM and lean into OSC). By doing so, a full list of associated directions to studies in the field of OSC is provided.Fig.8 also responds to thelast research question, and provides a new ground of argument for future research. The results are sought to demonstrate how future research on OSC, lean, and BIM can shape into various directions, but remain specific to associated research themes. These themes (e.g., project delivery process) are generated and formed from the earlier scientific mapping and qualitative analysis that highlight a range of studies that focused on OSC. As mentioned earlier in Section 5.3, the findings also demonstrate various methods of integrating OSC with other emerging construction concepts (e.g, BIM and lean). It is expected that the list of research themes can simply expand if more research areas are investigated. However, this study is limited to specific word search and only generate what is specifically given from the specific mapping. Hence, this allows for further research that can be conducted for individual research areas.



* DfMA stands for Design for Manufacturing and Assembly

Fig.8. Framework to link current research areas in OSC to future research directions

Some of the future directions (e.g., the SWOT analysis approach), asanticipated by Li et al. (2014), has been more widely performed recently. A context-specific example of such study is conducted by Jiang et al. (2018) for promoting OSC in China. Consequently, Yunus and Yang (2016) found that lack of incentive policy, insufficient governmental support, and fragmentation in the project delivery process caused barriers in implementing OSC. Other proposed directions by Li et al. (2014) are still in need of more studies, such as a holistic indicator system incorporating economic, social, and environmental perspectives in OSC. Key performance indicators (KPIs) proposed by Jonsson and Rudberg (2017) can be further expanded from the residential sector based on the production strategy perspective to a wider scope in the building industry sector from the project life cycle perspective.

The field of OSC, by its nature, encourages interdisciplinary collaboration involving both managerial and technical aspects, for example, the necessity of new project delivery process in a more integrated approach to minimize fragmentation. This also highlights the need to develop new technical standards to allow industry practitioners to adopt the right type of prefabricated components. New design standards such as DfMA (Yuan et al., 2018) are needed to ensure that off-site components meet the engineering property requirements, such as the seismic performance of modular steel components tested by Fathieh and Mercan (2016), and the structural behavior of connection joints between precast components (Park et al., 2017). In sum, this paper highlights the nature of integration in various research topics; for instance, based on the conducted science mapping and qualitative research analysis that resultin evaluating the co-occurrence analysis of keywords in the literature. This enables to also identify the synergies between various research fields and research topics, as highlighted in Section 4 of the study.

Finally, it is important to argue that readiness of stakeholders in moving forward with OSC needs to be set in the context of the local Architecture, Engineering, and Construction (AEC) market. This factor plays a major role to minimizing the gaps across these associated disciplines. For example, within the UK AEC industry, there is currently a predictability-continuity gap which makes companies unsure of investments in off-site manufacturing (Mann, 2017). This generally occurs due to multiple factors such as industry standard (e.g. procurement approach) and governmental policy. Industry practice now demands the BIM assistance to OSC, such as the coordination among plumbing and structural engineering designs. The DfMA-oriented parametric design incorporating multi-disciplinary design with

BIM as initiated by Yuan et al. (2018) could be an emerging research direction in the near future.

6. **Conclusion**

This review-based study in off-site construction adopted a holistic approach to achieve these four main objectives, namely: 1) identifying the latest research topics in the off-site construction domain; 2) summarizing the performance of off-site construction projects; 3) revealing the gaps in integrating off-site construction with other emerging construction concepts; and 4) providing directions for continued research in off-site construction. A scientometric analysis was firstly adopted to identify the latest research topics in the off-site construction domain within the recent decade. A total of *349* journal articles published in the recent decade were selected through a three-step holistic approach. It was found that the study in off-site construction has undergone two significant increases, i.e. from 2011 to 2012, and from 2015 to 2016. More importantly, it is expected that scholarly publications would continue growing in the following years. In this study, mainstream journals in the field of construction engineering and management, civil engineering, and architectural engineering that publish off-site construction research were identified. The most influential journals in off-site construction research could be different based on their measurement criteria. For instance, *Automation in Construction* topped the table in terms of number of publication, but *Energy and Buildings* was only ranked the highest in terms of citation per publication.

Co-occurrence analysis of keywords revealed these frequently studied research themes, including sustainability, lean construction, precast concrete, project planning and design, supply chain management, and BIM. Certain integration between BIM and sustainability, as well as between sustainability and lean construction were found in off-site construction. However, integration of multiple contemporary issues and optimization of project performance remain ongoing challenges in research. Other keywords such as project planning and design, transportation, and simulation indicated that research in off-site construction had been emphasizing the workflow and project delivery process, leading to further issues in standardization.

Active scholars and their research network were then summarized through scientometric analysis. The number of publications, the overall research significance quantified by total citation, and the research significance measured by average citation per article were topped by different researchers. Among these articles with highest citations, two were review-related, and others were related to RFID technology application, comparison between off-site construction and the conventional approach, as well as managerial issues of off-site construction within the context of a certain country or region (e.g., Hong Kong). Research active countries were also identified through science mapping. Both developed and developing countries (e.g., the U.S. and Malaysia) were found with significant contributions to the academic field of off-site construction. The U.S.-based scholars have received highest total citations, but researchers from Australia, mainland China, Iran, Canada, New Zealand, Hong Kong, and the UK played more influential roles to the global community of off-site construction according to their total link strength, average citation, and average normalized citation.

The follow-up qualitative discussion summarized the mainstream research topics within off-site construction, studied the performance measurements and indicators of off-site construction, evaluated the potential integration of off-site construction to other emerging construction concepts such as BIM, and proposed the framework guiding future directions. Off-site construction is a research domain that can be linked to multidisciplinary studies in terms of managerial, engineering, and technological perspectives. In the managerial aspect, existing studies have focused on the performance evaluation in terms of cost, scheduling, environmental sustainability, and safety. Critical success factors have been analyzed in affecting the performance, such as design coordination. From the engineering perspective, structural, thermal, and material properties of precast building components have been widely studied, especially the joint connections and behaviours of precast components under seismic loading. Using recycled materials (e.g., recycled aggregate) in precast components needs more studies in optimizing the properties of precast members. From the perspective of technology, BIM, RFID, and computational algorithms have displayed their capacity in assisting the implementation of off-site construction activities, such as simulating, optimizing, and evaluating the workflow of design, manufacturing, transportation, and site assembly.

Previous research had been largely focused on investigating the performance of off-site construction compared to that of conventional construction. Multiple performance indicators have been proposed, including financial, environmental, technical, and aesthetic aspects of off-site construction. Besides theoretical analysis (e.g., cost-benefit framework), there have been several case studies providing the empirical data of how off-site construction buildings performed differently. Critical factors affecting the performance of off-site construction projects were further studied, such as design coordination and risk management. A weighted performance indicator system would be needed to allow the comprehensive evaluation of project performance and to assist the decision making of stakeholders in adopting off-site construction approach. The performance indicator system required the empirical database of the multi-criteria performance of prefabricated projects.

Further gaps were found in the current off-site construction research. Firstly, failed integration of these contemporary construction engineering practices (i.e., emerging construction concepts) into off-site construction was identified as a gap. Although integrated project delivery, BIM, sustainability, and lean construction were supposed to be inter-linked in an off-site construction project, there have been insufficient research in integrating these practices. Barriers in implementing the integration could be further studied, such as in multi-party coordination in the design stage. Off-site construction demands new design system and standardization to ensure its successful implementation, leading to the concept of 'Design for Manufacturing and Assembly (DfMA)'. Similarly, limited studies have been found in linking DfMA into off-site construction. A holistic performance indicator system is needed to provide the comprehensive evaluation of off-site construction components and projects. Multiple factors would be included in this holistic system, including cost, social, and environmental indicators. Existing studies may turn out contradictory in their findings (e.g., cost performance), which could be due to the different country or cultural context. More data and/or case studies would be needed to enable the more comprehensive evaluation.

To summarize the main research topics within off-site construction, and based on the responses in addressing the research questions, directions for future research in off-site construction are proposed as shown below:

- An established framework allowing the input-to-output analysis of prefabricated construction in both the building component level and the project level;
- Studies on the mechanism of integrating BIM, DfMA, lean, and sustainability;
- Readiness of stakeholders in adopting off-site construction within a certain country or cultural context as well as the cross-country comparisons from a global perspective;
- A more holistic evaluation system of the performance of off-site construction from a larger database or more case studies;
- Application of integrated project delivery method in off-site construction addressing potential barriers (e.g., fragmentation);
- Development of technical standards and design codes for applying prefabricated components, as well as optimizing material sustainability and engineering performance.

This review-based study provides both academic and practical implication. Scholarly, this study contributes to the body of off-site construction knowledge by providing a focused perspective of the development of off-site construction research in the more recent decade. Key research areas were revealed, interactions of various key concepts were explored, and new directions were then uncovered. Methodologically, this study documented the way in which a bibliometric study approach is adopted in reviewing the off-site construction research. It demonstrated how a research area with a large number of literature could be more effectively reviewed by extending the bibliometric analysis to in-depth discussion. This study can also benefit industry practitioners by providing them the emerging practices in off-site construction practices, such as integrating BIM, DfMA, and lean in off-site construction. It would also lead to more future joint work between industry and academia such as performance evaluation of off-site construction projects.

It should be noticed that although this study attempted to synthesize the latest research within the OSC domain and to reflect the overall trend, some issues or practices in OSC that might have occurred are not captured because the methodology of this study relied upon the published literature. Furthermore, only English-written literature with keywordsin OSC and its variables were consulted. In another word, it may potentially exclude latest studies of OSCpublished in other languages.

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