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

Ruoyu Jin[a], Shang Gao[b], Ali Cheshmehzangi[c], Emmanuel Aboagye-Nimo[d]

[a]Senior Lecturer, School of Environment and Technology, University of Brighton, Cockcroft Building 616, Brighton, UK. Email: R.Jin@brighton.ac.uk

b shang.gao@unimelb.edu.au

[c]Associate Professor and Head of Department, Department of Architecture and Built Environment, The University of Nottingham Ningbo China, Centre for Sustainable Energy Technologies, Ningbo, China. Email: Ali.Cheshmehzangi@nottingham.edu.cn

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Abstract

Off-site construction has become an emerging research domain in the recent decade. Through a holistic review approach incorporating scientometric analysis and follow-up in-depth qualitative analysis, this study contributes to the body of knowledge in off-site construction by summarizing the latest research keywords and main research topics. This study also identifies the current gaps in research and practice, as well as proposing future research directions in this research area. Off-site construction 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 off-site construction. However, further research is needed in integrating the emerging digital construction technology, integrated project delivery method, lean construction, and the issues of sustainability of off-site construction. There are already limited studies linking off-site construction to the concept of Design for Manufacturing and

Assembly. Future research should also adopt a larger database and allow for comprehensive evaluation of off-site construction 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?

2. Review of current literature

Literature review is considered as an expedient approach to gain in-depth understanding of a research domain (He et al., 2017). 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. Researchers (such as …) believe that the findings of Hosseini et al. (2018) can be further extended to in-depth discussions (e.g., future research directions) following the science mapping of OSC-related publications. Therefore, a more holistic approach incorporating multiple methods can be adopted 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 select academic publications within the recent decade; 2) to apply the scientometric analysis in identifying the main research topics and gaps from the selected literature sample; and 3) to further extend the scientometric analysis by providing in-depth discussion of research topics, gaps, and recommendations in OSC. 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. In this research study, we first describe the holistic review of the methodology before presenting the results and initial findings through scientometric analysis. The paper then further explores the scientometric analysis by discussing the associated topics of research, gaps, and trends in OSC. The study finally concludes by providing a holistic review-based study.

3. Methodology

This study adopts an all-inclusive 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.

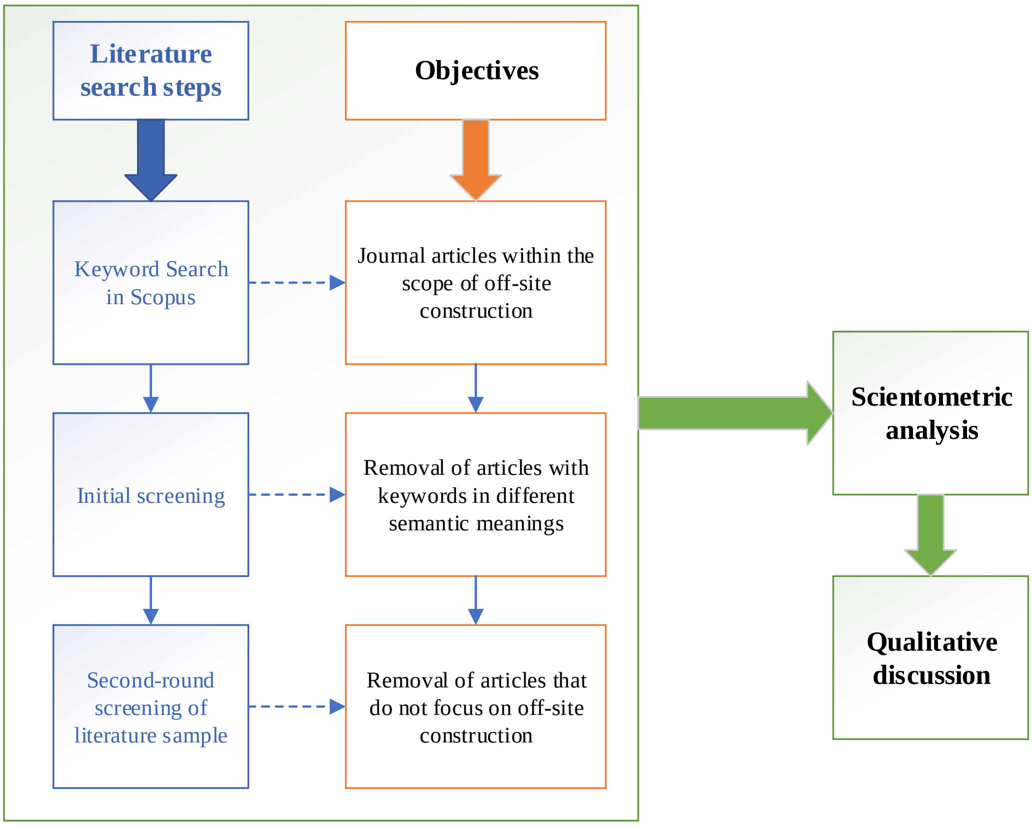


Fig.1. The workflow of OSC review in this study

As shown in Fig1, a systematic approach was adopted in order for the research objectives to be achieved. The workflow also demonstrates the individual stages were used systematically to arrive at a critical qualitative discussion.

3.1.Bibliometric analysis

Bibliometric search of OSC literature was performed in *Scopus*, which has been described by Aghaei Chadegani 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 (He et al., 2017; Oraee et 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 (Mao et al. 2015), such as ‘prefabricated construction’ or ‘modular construction’. By reviewing earlier studies (such as, Pan and Goodier, 2012; Cao et al., 2015; Mao et al., 2015; Hosseini et al. 2018), 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. Peer reviewed and non-peer reviewed conference papers were excluded, mainly because they have been published in a large quantity but less information has been gained by including them (Butler and Visser, 2006). 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.Science mapping

The text-mining tool, *VOSViewer* (van Eck and Waltman, 2010), was applied to generate the visualized map in OSC. *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. Zhao (2017) further stated that the scientometric method can be applied to other research areas. 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.

3.3.Qualitative discussion

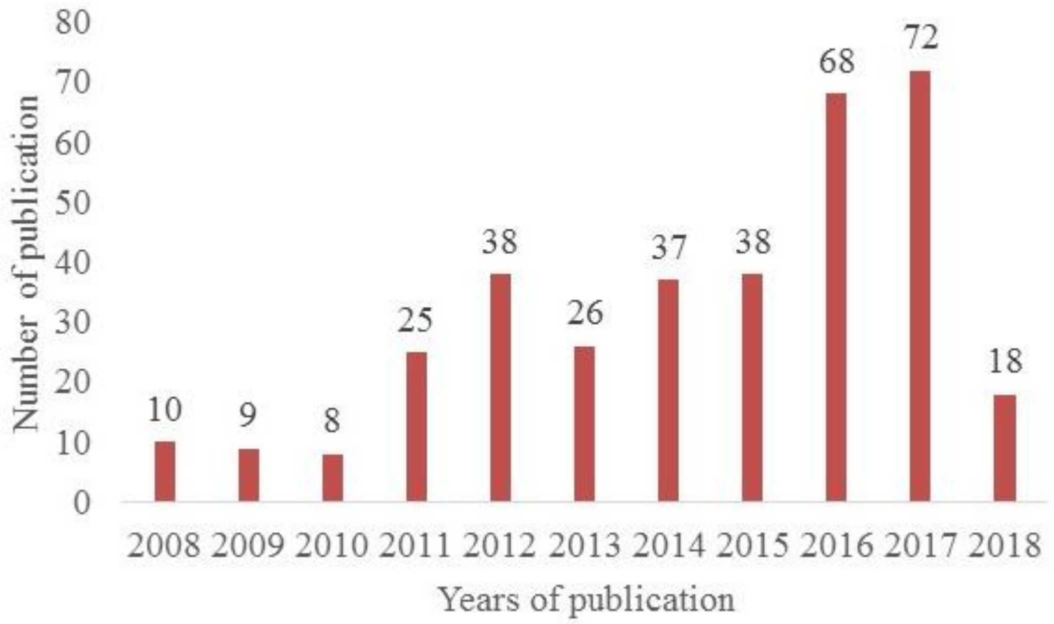
Following the bibliometric analysis and science mapping, a qualitative discussion was conducted to evaluate the current research focus areas in OSC. This approach was conducted to analyze the existing research trends, and to provide recommendations for near-future research in OSC. Current main research 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 Scientometric Analysis

By performing the bibliometric search in *Scopus*, originally a total of *1,212* journal articles published from 2008 to 2018 were found up to the date of 17 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 (Parreira Júnior and Penteado, 2018), chemistry (Fan et al., 2017), and biomedical material science (Medishetty et al., 2017). Even the keyword *prefabricated construction* could be ambiguous, as it might be in the context of a different field (de la Sota et al., 2017). Other articles (Zhao et al., 2018), which focused on product manufacturing without referring to the context of building construction or architectural design, were also removed from the literature sample. For the remaining articles with one of these key terms (such as *modular construction*) in their title, abstract, or keyword list, a second round of screening was performed to remove articles with 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 Jin et 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.



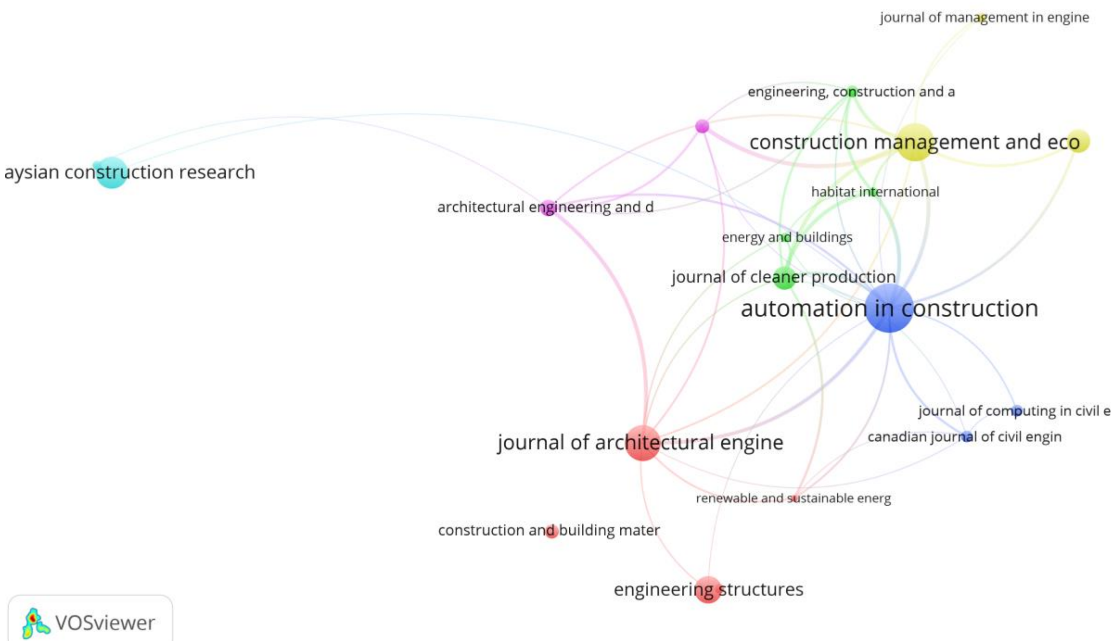
*Note: the number of journal papers in 2018 is incomplete as the articles selected in 2018 was up to the mid-February of 2018.

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 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*. 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***	**Number of articles**	**Total citations**	**Average citations**
Architectural Engineering and Design Management	22	7	33	5
Automation in Construction	53	22	277	13
Canadian Journal of Civil Engineering	8	5	22	4
Construction and Building Materials	1	6	66	11
Construction Innovation	20	6	54	9
Construction Management and Economics	51	17	221	13
Energy and Buildings	9	4	100	25
Engineering Structures	4	12	51	4
Engineering, Construction and Architectural Management	26	5	67	13
Habitat International	32	4	79	20
Journal of Architectural Engineering	36	16	209	13
Journal of Cleaner Production	36	10	95	10
Journal of Computing In Civil Engineering	4	5	25	5
Journal of Construction Engineering And Management	11	10	55	6
Journal of Constructional Steel Research	3	4	22	6
Journal of Engineering Science And Technology	7	4	43	11
Journal of Management in Engineering	4	4	68	17
Malaysian Construction Research Journal	9	14	58	4
Renewable and Sustainable Energy Reviews	14	3	53	18

* Total link strength corresponds to Fig.3 and indicates the interrelatedness between the given journal and other peer journals.

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. But the average citation per document could be without significant correlational relationship with other three measurements, indicating that the significance of a journal contributing to the research community of OSC is not necessarily related to its number of publications. According to 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*.

4.3.Co-occurrence of keywords

Keywords represent the key contents of existing research and depict the areas studied within the boundaries of a 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). By using “Author Keywords” and “Fractional Counting”, as recommended by van Eck and Waltman (2014), Oraee et al. (2017) and Hosseini et al. (2018), researchers can set the minimum occurrence of a keyword at *3*. In the output, initially *82* out of *1,129* met the threshold. Within these *82* keywords, some general keywords were removed, for example, “OSC”, “modular construction”, and “prefabricated construction”. Other keywords with semantically consistent meaning were combined, for example, BIM and “Building Information Modeling”, “IBS” and “Industrialized Building Systems”. Finally a total of *33* main keywords were shortlisted and visualised in Fig.4.

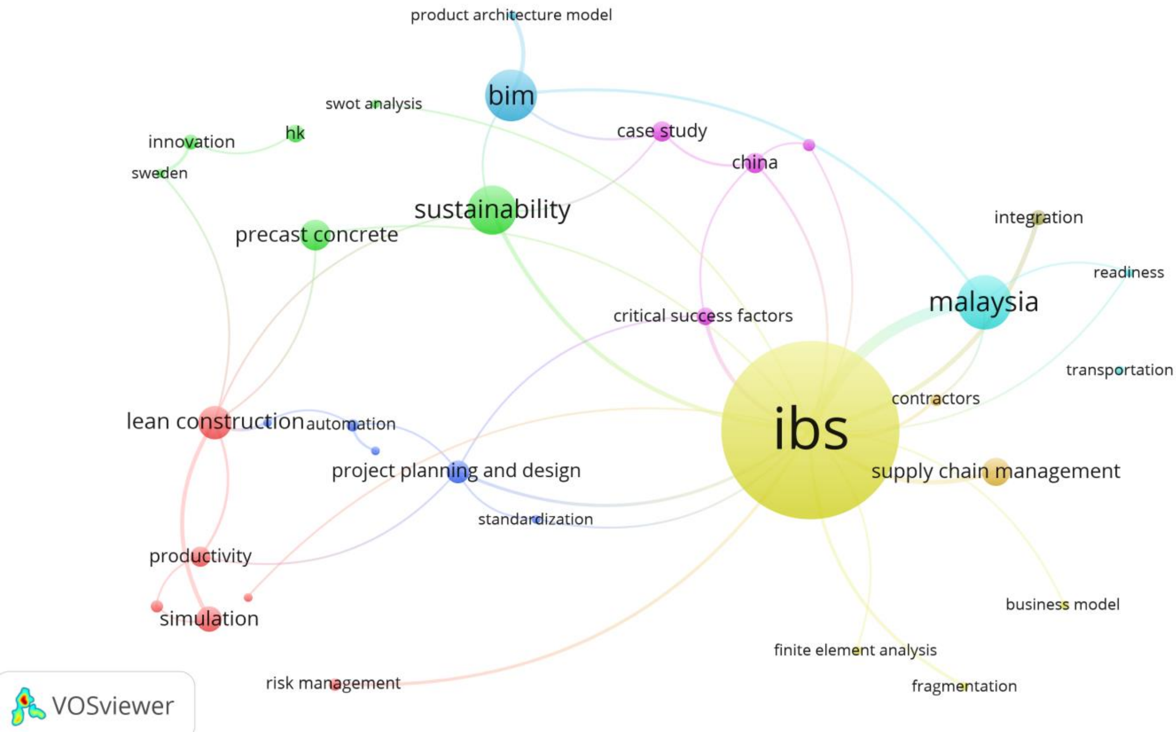


Fig.4. Co-occurrence of keywords in the research of OSC

It can be found from Fig.4 that IBS (i.e., industrialized building system) was the most frequently mentioned research keyword. Other keywords that most frequently co-occur with IBS include sustainability, critical success factors, Malaysia, and contractors. The clusters and connections lines among nodes of keywords in Fig.4 show these main research areas within OSC: 1) OSC has often being linked to lean construction (Arashpour et al., 2016), which is in the same cluster with productivity (Chen et al., 2017), simulation (Mitterhofer et al., 2017), and risk management (Shahtaheri et al., 2017); 2) OSC does not simply refer to the site assembly of building components, but involves the project design and planning (Choi et al., 2016), which is further linked to automation (Isaac et al., 2016) and standardization (Lei et al., 2015); 3) precast concrete is one of the commonly studied off-site manufacturing products; 4) OSC has been more frequently studied of its sustainability applications (Kamali and Hewage 2016), supply chain management issues (Wikberg et al., 2014), and critical success factors (CSFs) (Yunus and Yang, 2012); 5) case study (Gledson 2016, Wang et al., 2016) has been one of the main research methods in investigating CSFs in OSC; 6) several countries or regions have been active in researching OSC, including Malaysia, HK (i.e., Hong Kong), China, and Sweden. The readiness (Osman et al., 2017) of local industry to implement OSC has been a concern. SWOT (i.e., strengths, weaknesses, opportunities, and threats) analysis (Li et al., 2016) has been applied in the context of prefabricated construction; and 7) the emerging research and practice of BIM have been extended to OSC, such as applying BIM in establishing the product architecture model (Ramaji et al., 2017). Further studies such as observing the interconnections among BIM, lean construction, and sustainability reveals 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. But 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**
Automation	4	4	2015	6
BIM	10	19	2016	4
Business Model	1	3	2016	7
Case Study	5	7	2015	5
China	5	7	2015	14
Contractors	4	4	2013	5
Conventional Construction	2	4	2015	23
Critical Success Factors	6	6	2015	6
Finite Element Analysis	1	3	2014	6
Fragmentation	2	3	2014	10
HK (i.e., Hong Kong)	3	6	2013	27
IBS	45	71	2014	4
Innovation	3	5	2011	35
Integration	4	5	2014	7
Lean Construction	10	12	2013	14
Malaysia	19	20	2014	4
Mobile Crane	2	3	2014	7
Optimization	2	4	2017	0
Precast Concrete	3	11	2014	6
Product Architecture Model	3	3	2017	3
Productivity	4	7	2014	8
Project Planning And Design	7	8	2015	6

Readiness	2	3	2015	0
Risk Management	3	4	2012	9
Robotics	3	3	2012	5
Safety	3	3	2013	4
Simulation	6	9	2014	8
Standardization	2	3	2015	6
Supply Chain Management	4	10	2015	2
Sustainability	8	18	2014	7
Sweden	3	3	2013	13
SWOT Analysis	2	3	2015	3
Transportation	1	3	2015	3

Besides IBS, other most frequently studied keywords in OSC include Malaysia, 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) have been focusing 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 have been more recently 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 at 2011 or 2012.

These keywords, including innovation, HK, 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' 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, *39* out of totally *888* authors were identified from the co-authorship analysis. Fig.5 displays some of the main research collaborations among authors in the OSC domain.

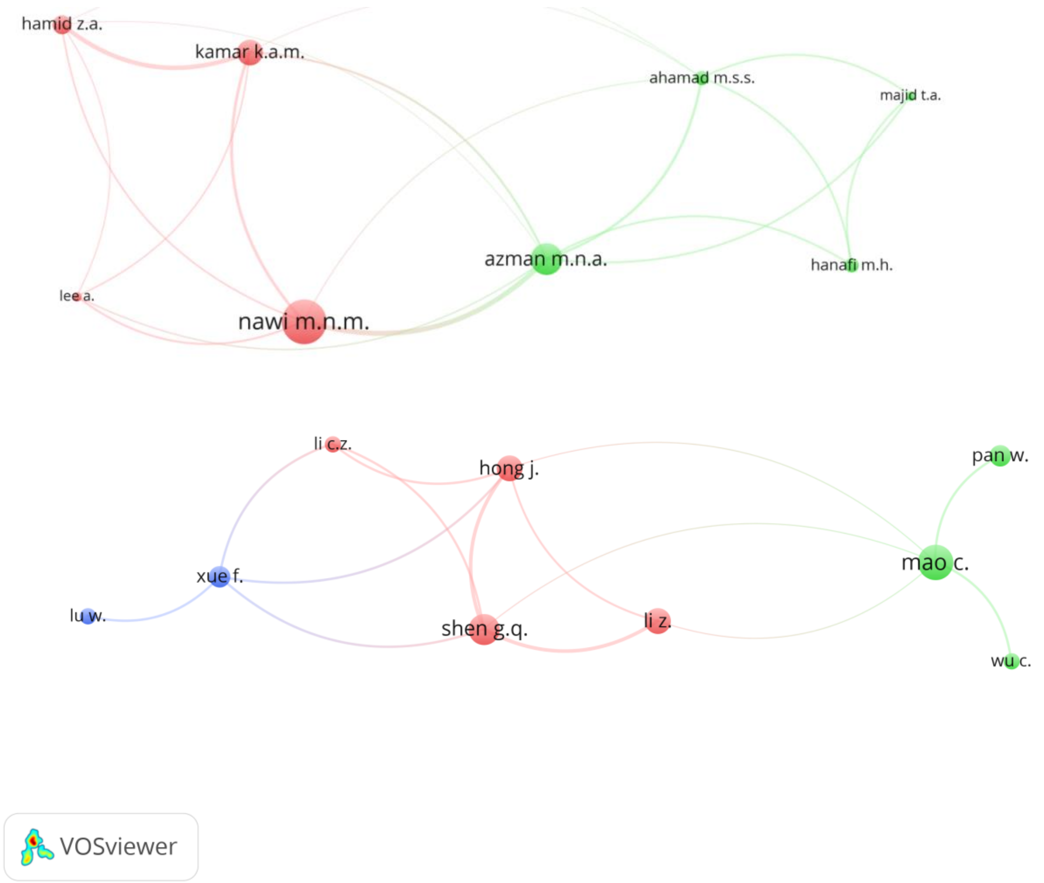


Fig.5. Co-authorship analysis

It can be seen in Fig.5 some authors and clusters have been both productive and collaborative in recent years, including the cluster of Nawi N.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. Quantitative summary of authors is provided in Table 3.

Table 3. List of active scholars in OSC research

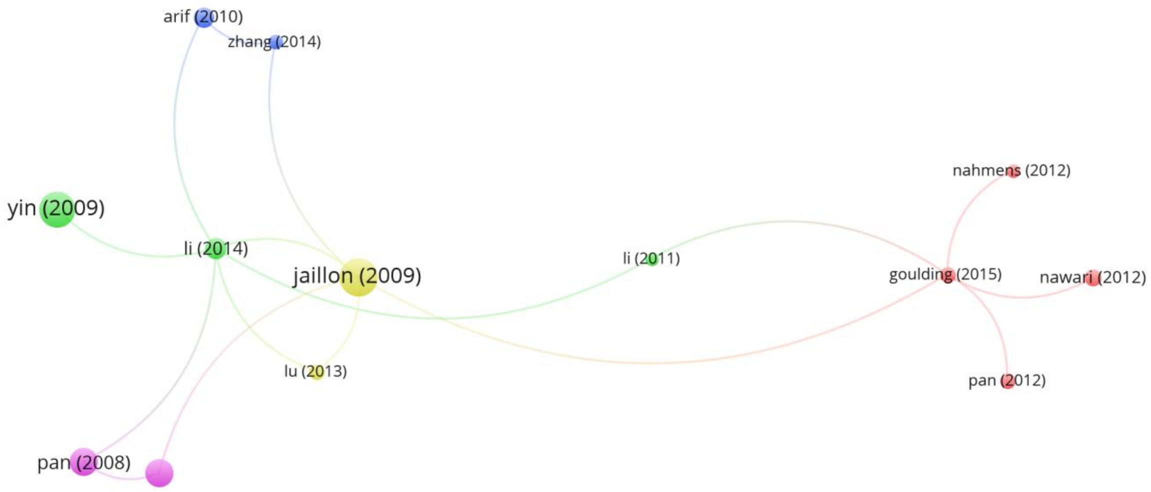
Author	**Number of articles**	**Total citations**	**Average publication year**	**Average citation**
Hong J.	5	43	2017	9
Li C.Z.	3	22	2017	7
Li Z.	5	62	2016	12
Lu W.	3	56	2014	19
Mao C.	7	106	2016	15
Pan W.	4	124	2012	31
Shen G.Q.	6	84	2016	14
Wu C.	3	35	2016	12
Xue F.	4	34	2017	9
Ahamad M.S.S.	6	34	2012	6
Azman M.N.A.	14	73	2014	5
Hamid Z.A.	8	65	2012	8
Hanafi M.H.	6	32	2013	5
Kamar K.A.M.	11	111	2013	10
Lee A.	4	61	2014	15
Majid T.A.	4	32	2011	8
Nawi M.N.M.	20	92	2015	5

A total of *17* productive authors are listed in Table 3. 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, most productive authors in the recent decade are Nawi M.N.M., Azman M.N.A., and Kamar K.A.M. But in terms of overall research significance, these authors top Table 3:

Pan W., Mao C., and Kamar K.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. Some scholars listed in Table 3 had established their research profile in OSC in earlier years, such as Majod T.A., whose average year of publication was 2011. More recently, these emerging scholars have made their contributions to the research community, including Hong J., Li C.Z., and Xue, F.

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 these totally *349* articles met the requirement. Fig.6 displays these articles with 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

(Goulding, Pour Rahimian et al. 2015)	New offsite production and business models in construction: priorities for the future research agenda	5	29
(Li, Shen et al. 2014)	Critical review of the research on the management of prefabricated construction	6	41
(Zhang, Skitmore et al. 2014)	Exploring the challenges to industrialized residential building in China	2	26
(Lu and Yuan 2013)	Investigating waste reduction potential in the upstream processes of offshore prefabrication construction	2	28
(Mao, Shen 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
(Pan and Goodier 2012)	House-Building Business Models and OSC Take-Up	1	29
(Nawari 2012)	BIM Standard in OSC	1	32
(Nahmens and Ikuma 2012)	Effects of Lean Construction on Sustainability of Modular Homebuilding	1	25
(Li, Guo et al. 2011)	Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong	2	25
(Arif and Egbu 2010)	Making a case for offsite construction in China	2	39
(Yin, Tserng et al. 2009)	Developing a precast production management system using RFID technology	1	74
(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
(Pan, Gibb et al. 2008)	Leading UK housebuilders' utilization of offsite construction methods	2	56

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. 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. 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.

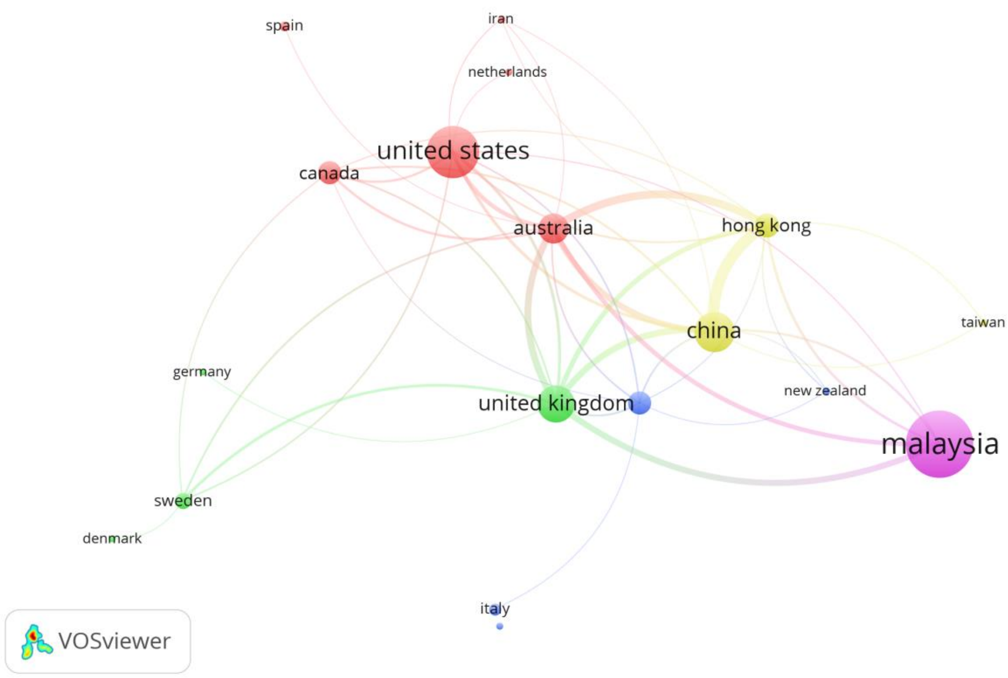


Fig.7. Mapping of countries where OSC researchers were located

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 U.K., 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. However, Malaysia, although high in publication number, forms its only cluster without sufficient inter-correlation with other countries (see Fig.7). The quantitative measurements of countries are provided in Table 6.

Table 6. Countries where PPP researchers are based

Country	**Total link strength**	**Number of articles**	**Number of citations**	**Average publication year**	**Average citation**
Australia	182	32	203	2016	6
Canada	42	23	184	2015	8
China	187	43	352	2016	8
Denmark	2	5	24	2013	5

Germany	5	5	21	2016	4
Hong Kong	181	25	382	2015	15
Iran	12	6	21	2015	4
Italy	6	11	54	2015	5
Malaysia	76	79	326	2014	4
Netherlands	7	5	67	2013	13
New Zealand	11	5	27	2015	5
South Korea	34	23	55	2016	2
Spain	4	9	148	2012	16
Sweden	31	15	183	2014	12
Taiwan	10	6	90	2014	15
Turkey	2	6	25	2012	4
United Kingdom	168	40	433	2013	11
United States	76	59	449	2014	8

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

Scholars from U.S. and Malaysia top Table 6 in terms of the number of publications. U.S. is also the country that has received the highest citations in OSC research. In terms of influence and mutual citations, these countries or regions (i.e., Australia, China, HK, and U.K.) 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, such as HK, Netherlands, Spain, Sweden, and Taiwan, have all generated important research outputs.

5. Qualitative Discussions

Following the scientometric analysis of journals, scholars, publications, and countries involved in the research community of OSC, qualitative analysis was carried out to summarize the main research topics, to identify existing research gaps, and to provide recommendations for future research.

5.1.Research topics within OSC

5.1.1. Precast concrete

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). Emphases have been given to comparing the 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, Hung 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 focusing on the structural performance of precast concrete components all displayed positive outcomes. The ongoing research and consultancy work in promoting the wider implementation of precast components would be towards establishing the design codes and standards.

Furthermore, 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 study of Ng et al. (2016) could lead to more studies in optimizing sustainability and structural performance in precast building components.

5.1.2. Performance measurement and indicators

A significant 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 project 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) found that more safety accidents occurred due to fall from working at height and suggested that safety programs and standards accommodate OSC. Despite the benefits of adopting modular construction according to these empirical studies, the practical cases may turn out more complicated, as not all executed modular projects have resulted in successful performance (Choi et al., 2016). Multiple CSFs affect the cost and scheduling 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).

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 and conducted by Osman et al. (2015). Integrated project delivery (IPD) was proposed as the approach to overcome the fragmentation in traditional construction (Nawi et al., 2014). Theoretically, IPD could boost the supply chain management in OSC. Research has been focusing on the workflow from manufacturing in factory, 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.

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 according to the case study of Nahmens and Mullens (2011). The lean construction practice was estimated by Court et al. (2009) to reduce 35% on-site labor and lower the site injury risks. In order to achieve the superior project performance, integration of multiple stakeholder and project parties in the design stage for OSC project is deemed a key factor (Othman et al., 2016). 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.

5.2. Current research gaps

5.2.1. 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.

5.2.2. BIM, lean, sustainability, and DfMA

BIM, lean construction, and sustainability have been attempted in their inter-relatedness to OSC (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 (Abanda, Tah et 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), is worth more 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 strongly closely associated with prefabrication (Laing, 2013). However, few studies have addressed the linkage between OSC and DfMA. There is a main gap in studying the DfMA and off-site manufacturing.

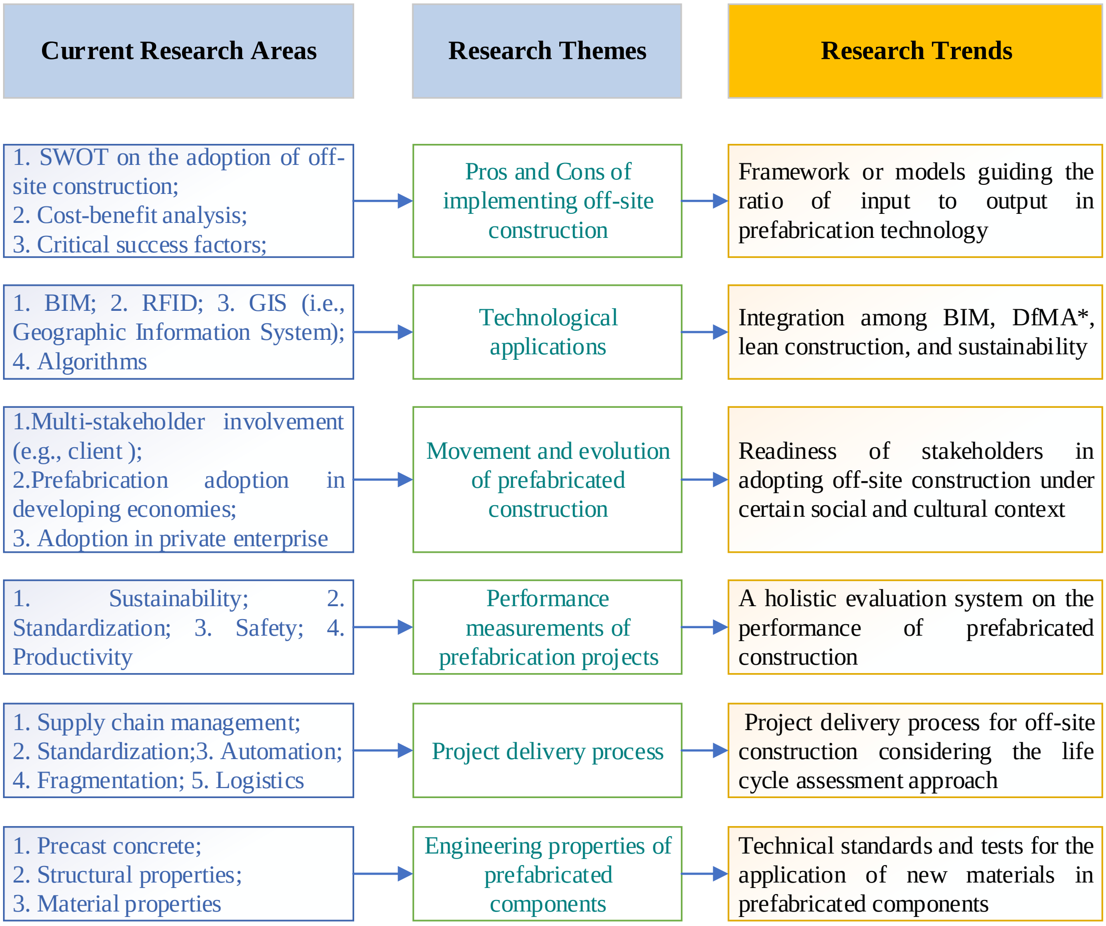
DfMA reflects the adaption of design systems from conventionally non-prefabricated buildings to cater to OSC. The adoption of prefabricated components demands the adaption of existing design standards and needs a better understanding of building performance, such as the tolerance in dimensional and geometric 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). More investigations are needed to not just compare the cost between industrialized buildings and conventional construction, but also the technical properties to gain a more comprehensive evaluation.

5.2.3. Holistic performance evaluation

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 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 crossing 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.Proposed research directions for OSC

Based on the qualitative analysis of current research areas within OSC and research gaps, the framework that links the existing studies to future directions is initiated in Fig.8.



*: 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 approach), as expected by Li et al. (2014), has been more widely performed recently. For example, Yunus and Yang (2016) found that lack of incentive policy, insufficient governmental support, and fragmentation in the project delivery process caused barriers in implementing IBS. Other proposed directions by Li et al. (2014) are still ongoing 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).

Readiness of stakeholders in moving forward with OSC needs to be set in the context of the local AEC market. For example, within the U.K. 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 scientometric analysis and in-depth qualitative discussion. A total of *349* journal articles published in the recent decade were selected through a three-step bibiometric 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 summarized through science mapping. 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 the 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, Hong Kong, and the U.K. played more influential roles to the global community of off-site construction according to their total link strength and average citation.

Following the scientometric analysis, the follow-up qualitative discussion summarized the mainstream research topics within off-site construction, identified the current research gaps, 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 behaviors 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.

Gaps were found in integrating these contemporary construction engineering practices into off-site construction. 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)'. However, limited studies have been found in linking off-site construction into DfMA. 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 or case studies would be needed to enable the more comprehensive evaluation.

To summarises, and based on the research gap analysis, 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.

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