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Review

Critical evaluation of off-site construction research: A Scientometric analysis

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ABSTRACT

Practical interest in 'off-site construction' has risen remarkably over the last decade, and with it there has been a burgeoning of academic research in the field. Complementing this research, a number of literature reviews have been conducted. None, however, are systematic. This study addresses this lack, offering the first bibliometric study to explore the state of off-site construction research (OCR). A quantitative approach using 'science mapping' techniques is employed to examine 501 top-ranked construction journal articles. Longitudinal trends in publishing are identified, as are dominant research sub-fields, their connectedness with other areas of study, as well as citation patterns, publication journal areas of focus, key research institutions, key research persons, along with the extent to which these interact with each other in research networks. The findings are instructive in identifying the deficiencies in current research. Among these is a bias towards product research over operations and management, and a sharp compartmentalization of sub-fields, with little or no cross-fertilization between researcher areas, the researchers themselves, nor the research institutions. Clearly, this awareness will inform industry, journal editors and researchers of the need for a deeper exchange of ideas in any future research efforts.

1. Introduction

Since the turn of the century, there has been a steady and growing interest within the architecture, engineering, and construction (AEC) industry in the adoption and development of off-site construction [1,2]. Similarly, as a scholarly domain, off-site construction research (OCR) has attracted considerable attention from researchers, with a consequent rise in related publications [3]. Despite the desirability of such attention, the accumulation of publications in the field presents certain challenges. Indeed, the volume of work now available makes it difficult to evaluate the exact nature of the knowledge uncovered, its impact and contribution, and specifically, to identify pivotal areas that remain overlooked or neglected. Yalcinkaya and Singh [4] argue that it is unclear as to what critical areas of off-site construction remain underresearched.

In essence, the field has seen a burst of research activity, and a rigorous, critical review of the body of output now available, is warranted. To date, this is lacking. Recent review studies on off-site construction, such as that by Li et al. [3] and Mostafa et al. [5] have been qualitative, and based on manual reviews. Despite their undoubted value, these are manual, qualitative reviews, prone to subjectivity, and restricted in their lack of reproducibility [6]. Markoulli et al. [7] point out that manual reviews explore the "trees," but do not present a broad overview of the "forest."

This study addresses this deficiency. It adopts structured, quantitative methods that generate a comprehensive, objective portrait of the existing state of research knowledge in off-site construction. The approach augments problem diagnoses, and facilitates the identification of remedial courses of action. Moreover, in highlighting neglected research niches, the findings may be used to inform future research directions in OCR; aiding research planning and funding efforts by policymakers and practitioners. As such, the study is predominantly an exploration of "what" questions found in the literature, rather than "why" and "how."

2. Background

Goodier and Gibb [8] define off-site construction methodology as

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"*…the process of manufacturing and preassembly of certain amounts of building components, modules and elements, prior to their shipment and installation on construction sites.*" Later, Quale and Smith [9] expanded the definition as "*…planning, design, fabrication and assembly of building elements at a location other than their final installed location to support the rapid and efficient construction of a permanent structure.*" The earliest recorded evidence of off-site construction date to 1624, when UK built units was sent across the Atlantic to the US. Later in 1790, in the absence of local craftsmen able to complete the work, timber-framed shelters were imported into Australia from the UK [10]. The advantages associated with the use of off-site construction compared with traditional on-site methods of construction, are well documented [11,12]. They include quality improvement, enhancement of structural reliability, increased productivity, shortening of construction time, and reduction of labor and material wastage [13–16]. Moreover, off-site construction is claimed to provide numerous environmental and social advantages, and as such is highly conducive to supporting sustainability initiatives [11,17]. There is also evidence of soft benefits; positive impact on health and safety, improved work conditions, and reduction in the need for working space and subcontracting [18–20].

These varied advantages provide an explanation for the rise in interest in recent years, in the implementation of off-site construction. In early 1996, the rate in Western European countries rose above 40%, while the size of the off-site construction industry in the UK almost tripled between 2004 and 2006 alone. Estimates show that around 57% of housing projects planned by 17 of the UK's largest housing associations will incorporate offsite methods [21]. Despite this, the application of off-site construction methods is limited [22,23]. Off-site construction represents 3% of the construction industry in Australia. In the US, over the period 2000–2014, the figure is 2–3% for new single-family houses, and below 1% for new multi-family houses [11]. In short, the field remains underdeveloped, small, immature, and sluggish [13,24]. Partially, this is attributable to the lack of knowledge regarding core concepts in off-site construction methodology [23,25]. As a result, a great deal remains to be done by researchers to spread the message, and to promote offsite construction methods as a viable alternative to the innovatively stagnant construction mainstream [9].

This deficiency has not gone unnoticed, with serious attention now being directed towards conducting research on off-site construction [3,9,26]. And, given the emergence of a plethora of published studies within OCR, several review studies have followed. These are summarized in Table 1. Using the precedent set by Cooper [27] for the classification of review studies, Table 1 categorizes these reviews as either "integration" or "criticism." Criticism papers provide a subjective appraisal by their authors on certain aspects of a phenomenon, while integration studies attempt to synthesize the findings of past literature towards drawing conclusions and providing insights [27]. Despite the great contribution made by these review studies in advancing OCR, a number of limitations must be acknowledged.

First, as illustrated in Table 1, and pointed out by Akmam Syed Zakaria et al. [23], existing review studies in OCR of the integration variety, have a narrow perspective. As an example, Akmam Syed Zakaria et al. [23] focused on factors affecting off-site construction adoption, whereas Mostafa et al. [5] reveal a bias towards application of lean and agile concepts within off-site construction.

Second, as again illustrated in Table 1, these studies incorporate the findings from only a small portion of available publications in OCR; hence, integration studies have very limited coverage. Third, as for studies falling within the criticism category, the integration and mapping of the literature itself, remains outside the scope of such studies. In any case, regardless of the objective, review studies within both the integration and criticism categories, are nevertheless driven by the reviewers' theoretical stance or by a predefined criteria for methodological validity [27]. Substantively then, all these reviews can be flagged as highly influenced by subjective judgment [6]. Thus, the case is made for conducting an objective quantitative review able to identify and plot

Table 1
Previous review studies on off-site construction.

Author(s) (year)	Method of analysis	Review categorization	Focus of study	No. of studies reviewed
Akmam Syed Zakaria et al. [23]	Manual literature review	Integration	A reviews of studied to integrate findings on different factors affecting off-site construction adoption	Not available
Boafo et al. [10]	Manual review of case studies	Criticism	To examine the general performance of modular prefabricated buildings based on existing cases and provide a dynamic case study-based review	N/A
Mostafa et al. [5]	Manual literature review	Integration	To develop a research framework for future studies on lean and agile integration within the offsite construction using the lens of simulation	62
Kamali and Hewage [11]	Manual literature review	Criticism	To critically review the research studies those have been carried out to evaluate the life cycle performance (preferably environmental) of modular construction.	106
Marjaba and Chidiac [22]	Manual literature review	Criticism	To review the state-of-knowledge pertaining to sustainability and resiliency metrics for evaluating buildings and off-site construction. Further evaluating the maturity of these metrics for adequately evaluating the sustainability and resiliency of different types of construction including off-site construction	N/A
Li et al. [3]	Manual literature review	Integration	To examine the current status (annual number of papers, contributions of institutions, adopted data collection and processing methods, research interest) and predicting future research trends in management of prefabricated construction	100
Jaillon and Poon [28]	Manual literature review alongside case studies	Criticism	To review the application and identify benefits and impediments of design for deconstruction and industrialized, flexible and demountable building systems when applied to precast concrete construction.	Not available
Lu and Yuan [29]	Manual literature review alongside case studies	Criticism	Examining the off-site CWS (construction waste sorting) practices in Hong Kong by drawing upon practical experiences of implementing the Off-site CWS program	Not available

the existing gaps in the literature in OCR from a meta-perspective. This, then, is the objective defined for the present study.

3. Research methods

The primary method used in the present study is 'science mapping.' This method was selected due to its proven capabilities in picturing systematic patterns in comprehensive bodies of literature and large bibliographical units [30]. Science mapping acts both as a descriptive and a diagnostic tool for research policy purposes, processing immense reservoirs of bibliometric data [31]. Science mapping allows researchers to conduct systematic literature-related discoveries by linking literature concepts that have been overlooked in manual review studies [32]. As this is the exact objective of this study, science mapping is the method most appropriate to this achieving this goal. Science mapping studies employ three overlapping, yet independent techniques: bibliometric analysis, scientometric analysis, and informatics. The focus of bibliometric analysis is predominantly on the literature per se, while scientometric analysis goes beyond this by measuring and analyzing the literature output to reveal the practices of investigators, and their socio-organizational structures [33]. As a broader approach, scientometric analysis covers bibliometric methods, tools, and data to assess the literature. Given the defined objectives, scientometric analysis was the primary method of the present study. As recommended by Börner [34], the research methodology was structured to comprise the following consecutive stages: selection of tools, data acquisition, pre-processing and analysis of data, modeling, visualization, and layout and communication of findings.

3.1. Selection of tools

A wide range of science mapping tools for bibliometric analysis are available [30] for mapping and visualizing a particular large-scale scholarly dataset in a knowledge domain [35]. The available tools for Scientometric analysis have different capabilities and strengths; thus, a thorough analysis of any field necessitates the use of several tools for different types of analysis [30]. To select the required tools for the present study, the features and limitations of various Scientometric software including VOSviewer, BibExcel, CiteSpace, CoPalRed, Sci2, VantagePoint [30], and Gephi were analyzed, leading to the selection of VOSviewer, CiteSpace, and Gephi. VOSviewer, with VOS the acronym for "visualization of similarities", is a freely available tool that offers the basic functionality needed for visualizing Scientometric networks [35,36]. CiteSpace is a scientific literature mapping tool which is capable of visualizing different layouts of networks, the detection of clusters, and emerging trends, including abrupt changes in the scientific literature, and producing cluster and time-zone views [37]. Gephi is an open source network graph and analysis tool at the forefront of the revolution in network visualization and analysis [38], which may be used to provide a thorough insight into the information achievable from a given network [39]. The various analyses conducted using these tools are described in detail in Appendix B.

3.2. Data acquisition

VOSviewer allows users to download bibliographic records directly from the Web of Science (WoS), PubMed, Google Scholar, and Scopus. From these options, Scopus was selected as the citation database for the present study. This was due to its relatively wide range of coverage, faster indexing process, and the availability of more recent publications, in comparison to the other databases [40].

A wide range of interchangeable terms are used by authors when referring to the concept of off-site construction across the global construction industry [41]. Several scholars have presented a list of these terms [13,41]. Searching within Scopus thus involved several possible combinations. The collection of terms identified by Mao et al. [41] and Cao et al. [13], in referring to off-site construction present as comprehensive, and the precedent set by them was deemed comprehensive for the purposes of this study. Consequently, the search terms in Scopus to retrieve the bibliometric data associated with published studies on off-site construction was as follows: "Off-site construction" OR "Off site construction" OR "Prefabricated construction" OR "Industrialized building" OR "Panelized construction" OR "Modular construction" OR "tilt up construction" OR "Precast" OR "offsite construction" OR "precast construction" OR "tilt-up construction."

Searching attempts using these keywords were conducted on the title, abstract, and keyword sections of published studies. The search had no timeframe limitation, with the date range criterion set to "All years to present." At this stage, the document type was refined based on limiting the search by applying "document title," to filter only articles published in top construction management journals. The rationale being that, for science mapping purposes, articles in high-ranked journals represent the most influential research studies [42]. Conference papers are published in large numbers, and little is gained by including them, given the extra level of complexity added to the analyses [43]. Besides, many review studies in the construction management domain have conducted their research studies based solely on articles in top ranked journals [44]. There is thus consensus within the profession regarding the preferability of picturing research within a field based on articles published in top ranked journals [42]. The list of journals (as illustrated in Appendix B) comprised 22 construction journals, collated and identified in previous review studies [3,45]. It is worth noting that the findings are based on the dataset extracted from Scopus, and therefore carry with it any inherent limitations of Scopus' terms of coverage and indexation of published studies. That said, inclusion of all of the relevant literature on a topic of interest, while ideal, is challenging and costly. Consequently, adequacy of data acquisition is deemed acceptable in review studies, since the key trends will be adequately uncovered, while a clearly specified sampling methodology ensures the search strategy is transparent and reproducible [46].

As of 5th June 2017, 501 journal articles were identified, for which all bibliometric data were extracted and downloaded from Scopus, forming the dataset utilized in the present study.

3.3. Scientometric techniques

Science mapping, in the present study, was performed in two consecutive stages. The first stage entailed the creation of networks through analyzing the co-occurrence of keywords, and undertaking document co-citation analysis, citation burst analysis, direct citation analysis of outlets, and co-authorship analysis, with the details described in Appendix A. In view of the study's objectives, these techniques were considered the most effective: interested readers are referred to Cobo et al. [30], van Eck and Waltman [36], and Chen [37] for full descriptions of these techniques. Their widespread acceptance and recommendations for their use in the construction field in studies of a similar nature [47,48], further justified the use of these techniques.

In the second stage, network analysis generated maps in order to extract useful information from the measures of the network. These measures showed "the conceptual, intellectual, or social evolution of the research field, discovering patterns, trends, seasonality, and outliers" [30].

4. Findings of the study

4.1. Wave of research on off-site construction

The first study on off-site manufacturing within the dataset turned out to be the study by Pollner et al. [49], published in the "Canadian Journal of Civil Engineering," where off-site manufacturing was referred to as "recent," with a focus on structural engineering aspects. Fig. 1 shows the variations in the total number of publications on off-

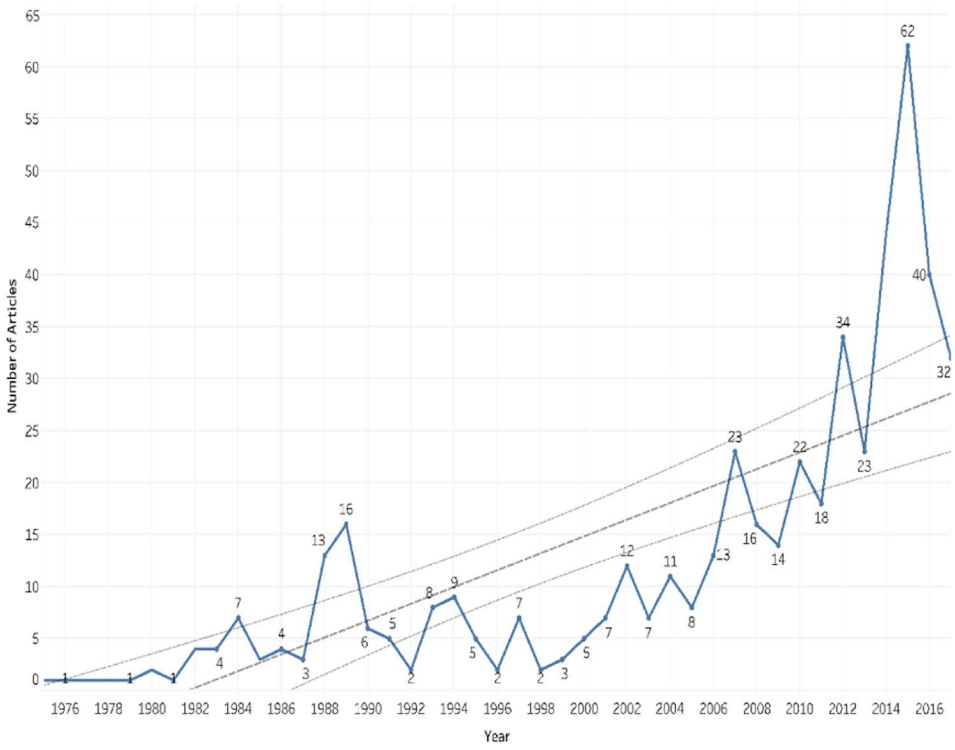

Fig. 1. Variations in the number of published studies on off-site construction (1975–2017).

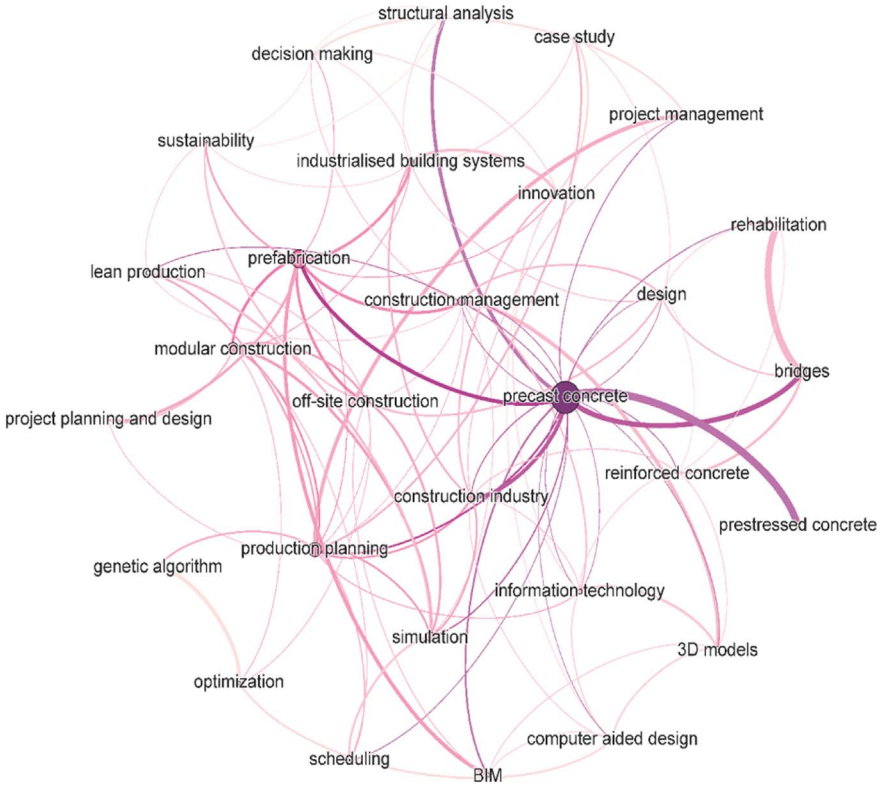

Fig. 2. Main research areas in off-site construction field and their relatedness

site manufacture over the period 1975–2017. As can be seen, the findings demonstrate a gradual and steady rate of increase in interest in OCR from 1975 onwards. This appears promising, indicating an area of research still active after four decades. Nevertheless, the concept of 'research ageing' needs to be taken into account. The term refers to the period of time after publication within which a research study remains influential and suitable for citation in subsequent studies. Evidence suggests that studies age, losing relevance after some 10 years [50]. In view of this, the four decades of history in this field points to a discontinuity between conversations in recent studies and those of the earlier debates of the 70s and 80s.

There exists a burst in the number of published studied during the period 2012 to 2015. This sudden increase in the number of publications on off-site construction within the last few years was identified

and discussed by Mostafa et al. [5].

The increasing trend coincides with the publication of the research roadmap for off-site production and manufacturing in 2013, by the CIB Task Group TG74 [51]. The generic trend, however, looks likely to be winding down, with 2016 showing a trend correction in terms of the number of articles published. This is due to the fact that the publication of generic articles has reached saturation point in construction journals, with the current need now for more technical articles, focusing on engineering solutions [52].

4.2. Structure of the body of knowledge in OCR

4.2.1. Main research areas (co-occurrence of keywords analysis)

Keywords represent the core content of published studies and depict the range of areas researched within the boundaries of any domain [32]. A network of related keywords provides an accurate picture of scientific knowledge production in terms of patterns, relationships, and intellectual organization of the topics covered [36]. Therefore, a co-occurrence network of keywords was created using VOSviewer. The weight of the link between two keywords is calculated based on the number of publications in which both keywords occur together [36]. VOSviewer forms this network by considering the closeness and strength of existing links. The network was created by VOSviewer, subsequently submitted to Gephi for further analyses. Using Gephi, similar terms (such as “precasting”, “precast”, and “precast concrete”) were merged, and generic terms such as “China” were omitted. A network comprised of 29 nodes and 106 links, as shown in Fig. 2, was created, illustrating the main areas of research identified in off-site construction research

Much of the work involved in extracting information from a network involves calculating network measures. The simplest and most reliable approach to measuring the centrality of a node in a network is calculating its “degree centrality.” By calculating importance based on the number of connections, this indicates the influence of a node on other nodes. A modified version of degree centrality, “weighted degree in the network,” takes into account the average mean of the sum of the weights of the links on all the nodes in the graph. Opsahl et al. [53] argues that incorporating the weight of links into calculating degrees will reveal the focal points or the level of involvement of nodes in a given network. The results of the analyses on the network are presented in Table 2. The ranking of the main research areas, as shown in Table 2, and the relatedness of the research areas, as demonstrated in the map of Fig. 2, reveal several interesting findings, reflecting gaps and problems with the literature in OCR.

I. Despite the fact that OCR covers a wide range of subcategories of research and is referred to by different terms [41], Table 2 reveals a special focus on several of these areas, and with less attention on other subcategories. That is, *prefabrication*, *precast concrete*, and *modular construction* have been highly influential in OCR, whereas less attention has been paid to *industrialized building*, namely, strategic aspects of OCR. In essence, hardware aspects of OCR have been by far more influential compared with managerial and strategic aspects of OCR, denoting a lack of attention to these areas within the existing literature.
II. It is revealed from the findings that the existing mass of research has a bias towards “product” aspects and hardware features of OCR, rather than “operational” and “process” facets. Project management, optimization, scheduling, and project planning are ranked very low, whereas product-oriented features such as concrete and production planning are central to the network of OCR (see Fig. 2) with strong links to structural analysis, and pre-stressed concrete. This finding accords with the observation above regarding the lack of attention to strategic areas, such as industrial buildings. This may be because, embracing the idea of industrialized building requires resolving the issues of processes, decision making, planning, etc. [23]. These nevertheless have not received the level of attention they deserve within the existing literature in OCR.
III. As an unexpected finding, sustainability and lean production fall within areas where limited attention has been devoted (see Fig. 2), and are almost entirely isolated from relevant areas of investigation in OCR. As an example, the link between sustainability and optimization is non-existent. In fact, optimizing processes sit at the center of sustainability aspects related to waste reduction and intelligent consumption of resources, and are presumed to be strongly linked with OCR [22]. Moreover, existing studies have failed in utilizing the potentials offered through BIM in enhancing sustainability, while BIM, lean, and sustainability are inherently overlapping concepts with much to offer from their integration [54].
IV. BIM, information technology, computer aided design, 3D Models are linked together. These areas however are not positioned as central areas of research in OCR. Although this might be partially attributed to the novelty of BIM literature, there is great potential for BIM to facilitate OCR [55], hence lack of research studies that integrate BIM and OCR is to be treated as a serious gap within the existing literature in OCR. This problem is reflected in industry practices. This is because, for off-site construction, “integration of process with BIM” is still seen as a barrier to widespread implementation [24].

Table 2
Central focus of OCR.

Research area	Degree centrality	Weighted degree centrality	Relative importance
Precast concrete	24	23.00	1
Prefabrication	11	13.67	2
Production planning	14	11.25	3
Modular construction	10	9.50	4
Bridges	4	8.50	5
Construction industry	10	8.17	6
Simulation	8	8.00	7
Off-site construction	10	7.75	8
Construction management	11	7.50	9
Industrialized building systems	9	6.50	10
3D models	6	5.50	11
Innovation	7	5.17	12
Information technology	9	5.17	13
Lean production	8	5.00	14
Design	9	5.00	15
Rehabilitation	4	5.00	16
BIM	5	4.50	17
Optimization	4	4.00	18
Pre-stressed concrete	1	4.00	19
Project management	4	4.00	20
Computer aided design	7	4.00	21
Reinforced concrete	7	4.00	22
Decision making	7	3.50	23
Sustainability	6	3.50	24
Case Study	4	3.00	25
Genetic algorithm	2	3.00	26
Structural analysis	4	3.00	27
Scheduling	4	2.83	28
Project planning and design	3	2.67	29

4.2.2. Patterns of citations (documents co-citation analysis)

Patterns of citations among published studies, in terms of the groupings formed by accumulated co-citation trends, provide an insight into the structure of a scientific knowledge domain. This is based on the assumption that clusters of co-citation reveal the underlying intellectual structure of a domain of research, with cited documents as concept symbols [56]. The most common approach to acquiring this information is to form a network of document co-citations to create clusters of citations. In this regard, CiteSpace is an effective computing tool

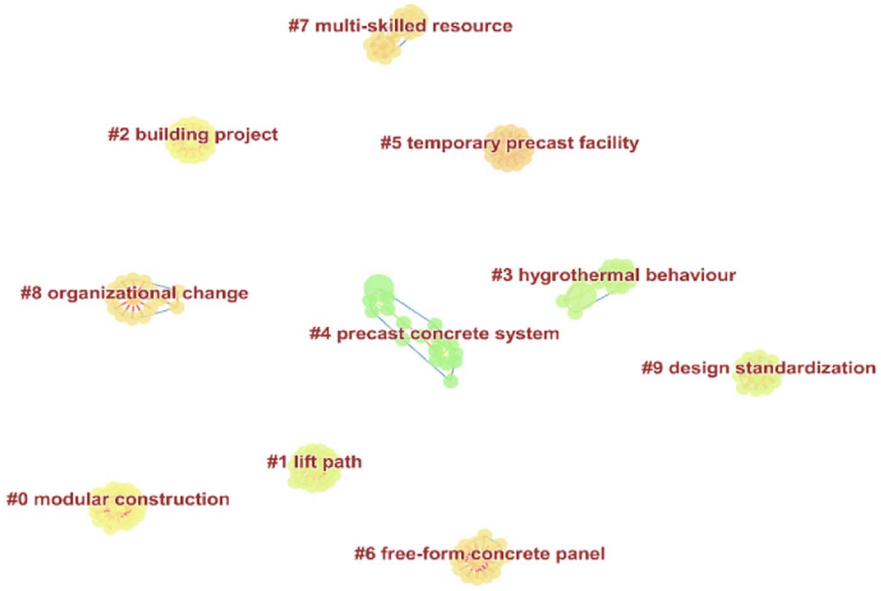

Fig. 3. Clustering structure for off-site construction research.

Table 3
Patterns of citations and main citation clusters (see Fig. 3).

Cluster ID	Size	Silhouette value	Mean (Year)[a]	Focus of the cluster
0	21	1	2011	Modular construction
1	18	1	2010	Lift path
2	17	1	2011	Building project
3	17	1	2008	Hydrothermal behavior
4	17	1	2006	Pre-cast concrete system
5	16	1	2013	Temporary precast facility
6	16	1	2012	Free-form concrete panel
7	16	1	2012	Multi-skilled resource
8	15	1	2012	Organizational change
9	14	1	2010	Design standardization

[a] Note: This shows the average year of citations in the cluster.

[56,57]. The result of the clustering is illustrated in Fig. 3, demonstrating the formation of ten noteworthy clusters, where cluster #0 is the largest, and cluster #9 is the cluster in which the smallest number of studies is included (see Table 3). CiteSpace proposes labels for the identified clusters (see Fig. 3). Yet, as argued by Chen et al. [56], in this type of analysis, much of the attention is on the structure of the clusters, rather than on focusing on their content.

In addition to visualizing the structure of the clustering, CiteSpace assessed the details of the overall citation network with a modularity value of $Q = 0.9104$. As asserted by Chen et al. [56], networks with modularity values close to 1.0 represent cases where components of the network are isolated. As such, OCR represents a network with dense connections between the studies within each cluster, but sparse connections between studies in different clusters. The details of these clusters were extracted from CiteSpace, as illustrated in Table 3.

The silhouette value reflects the uncertainty in defining a cluster [56]. The values corroborate the findings based on the modularity value of $Q = 0.9104$ for the network. That is, according to the reference values provided by the seminal study by Rousseeuw [58], silhouette values close to 1 suggest that the clusters are homogeneous; namely, an object is quite similar to its own cluster compared with other existing clusters. With regard to these findings (Fig. 3; Table 3), the following observations are worth noting:

V. The findings indicate that out of 501 studies included in the analysis, 167 were found to be in noteworthy clusters. As such, compared to the total number of studies in the network, as illustrated in Fig. 3, OCR can be described as a field where 67% of studies belong to no cluster and merely form a fragmented network. As such, where a major part of the studies belong to no cluster of citation than its own, there is an endemic problem with OCR in terms of a lack of focus, exchange of ideas, and debate among investigators.
VI. Given the isolation of clusters in Fig. 3, publications on off-site manufacturing form clusters that are isolated and disjointed from each other. In view of the values for silhouette calculated for each cluster, it can be concluded that clusters in the network are almost entirely connected through intra-cluster citations rather than through citations with studies outside their clusters. This indicates researchers' disregard for borrowing applicable theories and findings from studies outside their cluster. According to Hicks [71], such homogenous clusters are created when authors do not cite studies from outside the cluster. As such, research studies created in each cluster do not draw on a wide range of sources of knowledge [59]. OCR's existing citation clusters are inward-looking, hence do not benefit from theories and ideas from other research domains. Based on the arguments put forward by Zahra [60], this observation identifies OCR as a scholarly domain of research with a serious credibility flaw.

4.3. Top research outlets (direct citation analysis of outlets)

Direct citation analysis of outlets in any field of research offers an indication of the prominence of outlets in the given area, with recent studies showing a growing interest in using direct citation for bibliometric network creation [36]. Identifying the key outlets of off-site construction research may be of value to readers in terms of identifying the best resources, and to authors in terms of identifying the best outlets for publishing. On the other hand, this information may be of value to the editors of journals in relation to strategic planning and in making adjustments to their objectives, and in directing institutions and libraries in how best to allocate scarce resources in regards to buying the best outlets [61]. In the present study, a network was created based on the direct citation analysis of outlets with the details described in Appendix A, and visualized through deploying Gephi, as illustrated in Fig. 4.

The hyperlink-induced topic search (HITS) algorithm was used to analyze the network and rank the actors in the network (the outlets) based on their hub score level. The HITS algorithm gives a different hub score to each node as an indicator of the number of highly informative nodes to which a particular node is pointing. Hence, a high hub score

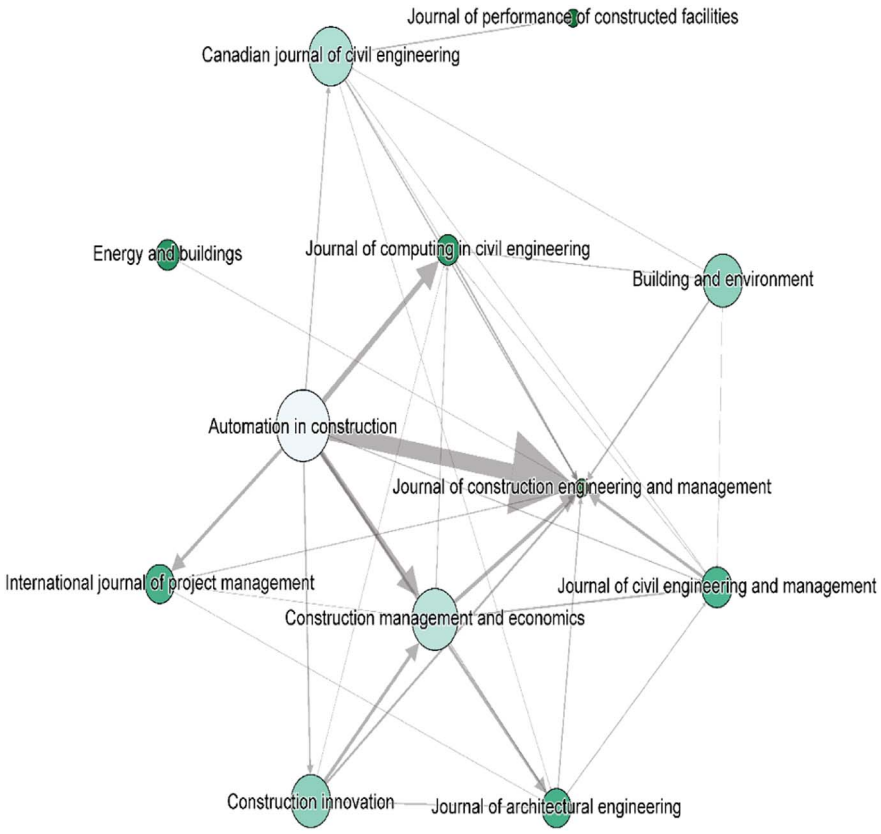

Fig. 4. Network of prominent outlets for publications in OCR
Note: Higher hub scores are shown with larger circles in lighter colors.

shows that the node in question serves as a directory and a key reference source to the nodes in the network [39]. The hub score was utilized to resize and recolor the nodes in the network as illustrated in Fig. 4, with lighter and larger nodes indicating higher hub scores. Table 4 illustrates the top 12 outlets in OCR, ranked based on their hub score in the network. Table 4 also illustrates the out-degree scores of the outlets, with this being a measure for ranking the importance of nodes in networks. This evaluates a score based on the number of outgoing associations for each node in any given network [39]. Both these scores (hub and out-degree) show similar ranking positions for the outlets included in the network.

As illustrated in Fig. 4 and Table 4, *Automation in Construction*, with a hub score of 0.519, stands out as the most prominent outlet for OCR. *Construction Management and Economics* (hub score 0.423), *Canadian Journal of Civil Engineering* (hub score 0.40), *Building and Environment* (hub score 0.338), and *Construction Innovation* (hub score 0.338) were also outlets with relatively high hub scores.

To acquire a better understanding of the focus of published studies in each outlet, bibliometric data for each outlet was submitted to VOSviewer separately and the main areas covered by publications in each journal were extracted, as illustrated in Table 4.

The most important point in selecting a journal, concerns the “fit” between the journal and the manuscript [62]. Given the need to avoid rejection and the loss of time, “fit” is the most basic consideration in submitting a manuscript to a journal, according to Knight and Steinbach [62] model for journal selection. It can therefore be concluded that studies published in different outlets are in close alignment with the aims and objectives of the outlet. Based on the facts above and in view of the focus of the studies by the prominent outlets in the area, several facts related to the OCR literature come to light. This is discussed next.

VII. The flow of information starts from *Automation in Construction* with a weighted out of degree value of 88, well above any other outlet in the list (see Table 4) and a focus on mathematical methods of production optimization. As judged from the areas covered by other outlets, support for the technical and hard requirements and studies focused on concrete and product are among the majority of published papers in prominent outlets in OCR. However, widespread use of off-site construction requires a change of practices in a broader sense of people, process, working culture, communication, business models, etc. [23,63]. As illustrated in Fig. 4 and Table 4, except for *Construction Innovation*, prominent outlets have not been influential in advancing such arguments in OCR. This has created a significant gap in the where OCR prominent outlets placed hard requirements above soft needs.

VIII. The appearance of civil engineering-oriented journals (Canadian Journal of Civil Engineering and Journal of Civil Engineering and Management) above outlets such as International Journal of Project Management further corroborates the observation regarding the lack of attention towards project management and managerial areas of OCR compared against design of products.

IX. Sustainability aspects and areas are limited to few outlets such as *Building, Environment and Energy and Buildings*, and *Journal of Architectural Engineering*. This focus however is biased towards narrowed areas of sustainability, particularly energy efficiency and thermal attributes of buildings. In essence, sustainability has not received much attention from prominent outlets in OCR judging from the main areas of focus, as illustrated in Table 4.

4.4. Scientific collaboration networks in OCR (co-authorship analysis)

Awareness of the existing scientific collaboration networks in any field of research facilitates access to funds, specialties, and expertise; enhances productivity; and assists investigators to reduce isolation. This ultimately benefits scientific collaboration and boosts scholarly communications [64]. “Almost every aspect of scientific collaboration

Table 4
Top OCR outlets.

Rank	Journal	Published studies	Hub score	Weighted out of degree value	Main topics covered
1	Automation in Construction	55	0.519	88	Genetic algorithm, optimization, precast production, BIM
2	Construction Management and Economics	31	0.423	8	Precasting, production planning, industrialized building, prefabrication
3	Canadian Journal of Civil Engineering	63	0.4	9	Bridges, pre-stressing, rehabilitation, reinforced concrete
4	Building and Environment	18	0.338	17	Cradle-to-cradle, green house emission, lifecycle assessment, air permeability, air-tightness
5	Construction Innovation	10	0.338	18	Design and theory, stakeholders, Decision making
6	Journal of Civil Engineering and Management	15	0.221	1	Compression test, precast concrete, precast prefabrication
7	International Journal of Project Management	12	0.205	3	Decision making, delay, integration, performance measures, workflow variance
8	Journal of Architectural Engineering	26	0.205	5	Manufactured construction, precast, panels, sustainability, lean construction
9	Energy and Buildings	18	0.124	8	Precast concrete, R-value, thermal performance, thermal resistance
10	Journal of Computing in Civil Engineering	17	0.124	4	Information technology, 3D models, scheduling, simulation, prefabrication
11	Journal of Construction Engineering and Management	91	0	0	Construction management, prefabrication, project planning and design
12	Journal of Performance of Constructed Facilities	58	0	0	Concrete, precast, non-destructive test, precast concrete

networks can be reliably tracked by analyzing co-authorship networks" [65]. Co-authorship is shorthand for scientific collaboration, with the lack of collaboration in a scientific network seen as a symptom of lower research productivity. In other words, ample evidence demonstrates that publications produced through collaboration are published in outlets with higher impact and receive more citations, a point argued at length by Glänzel and Schubert [65]. With this in mind, the next section presents an analysis of the co-authorship network of investigators active in OCR.

4.4.1. *Prominent investigators*

The network was created, as described in Appendix A, and visualized (see Fig. 5). As illustrated in Fig. 5, two noteworthy collaboration clusters were identified with several partially clusters which involved two authors. Each cluster shows a group of investigators connected directly through publishing papers together or indirectly via having common co-authors. The HITS algorithm, as described by Khokhar [39], was deployed to rank the actors in the network (the authors) based on their authority scores. The HITS algorithm is a reliable technique for ranking influential sources of information in a network, with higher authority values indicating popular and heavily linked actors. A high authority score also depends on the quality of the connected actors of a node, with a high score showing that the actor is linked with other influential actors of the network [66]. Authority scores were utilized to resize the nodes on the network, as illustrated in Fig. 5, with larger nodes indicating higher authority scores. As a result, Fig. 5 presents a map of the collaboration network of investigators undertaking research within OCR, an evaluation of the authority of investigators involved in the network, and the strength of the associations between investigators. The findings that come to light based on the map in Fig. 5 are discussed below.

X. The two identified clusters show a "linked research enterprise", a term introduced by Newman [67]. Overall, this seems to be a promising picture, as it shows that there are clusters for constant exchange and creation of knowledge through collaborative research in OCR. Fig. 5 nevertheless reveals an intellectual isolation for many authors within the network. To be specific, many authors do not belong to any cluster. This warrants more effort to form existing partially formed clusters into linked research enterprises, highlighting an area in need of attention.

4.4.2. *Top institutions*

Apart from the collaboration activity of individual investigators, identifying the collaboration network of the institutions with high interest and investment in OCR benefits the field, particularly in terms of providing input into research partnership policy making [64]. This network was created, as described in Appendix A, and visualized as in Fig. 6. The HITS algorithm was utilized to create the hub scores for institutions. As previously mentioned, the hub score reflects the number of highly informative nodes to which a particular node is pointing [39]. Hence, a high hub score for an institution shows that it serves as a directory to other institutions involved in research. The size of the nodes and the color range were adjusted to reflect the hub scores, with larger nodes and lighter colors indicating higher hub scores, as shown in Fig. 6. The distance-based map in Fig. 6 illustrates the closeness of institutions in terms of collaboration as well as their score for acting as a hub.

The institutions identified in the present study are in close alignment with the findings of the study by Li et al. [3] who presented a list of prominent institutions active in OCR. *Hong University of Science and Technology* stands out among other institutions in view of the number of published studies, alongside the level of collaboration with other institutions in the field.

XI. Nevertheless, the level of collaboration among a major part of

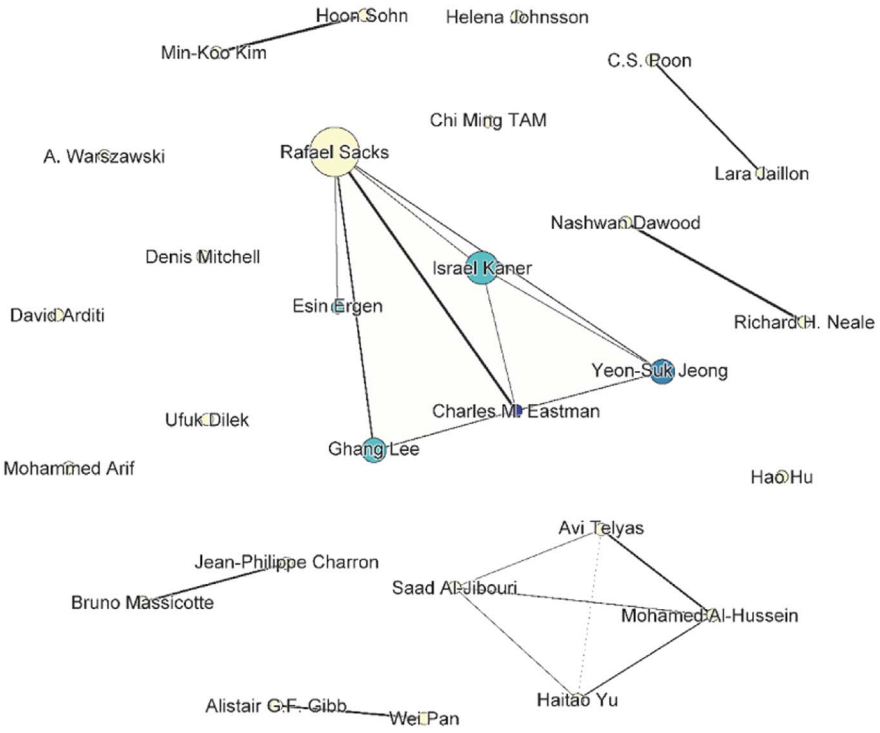

Fig. 5. Collaboration network of investigators in OCR.

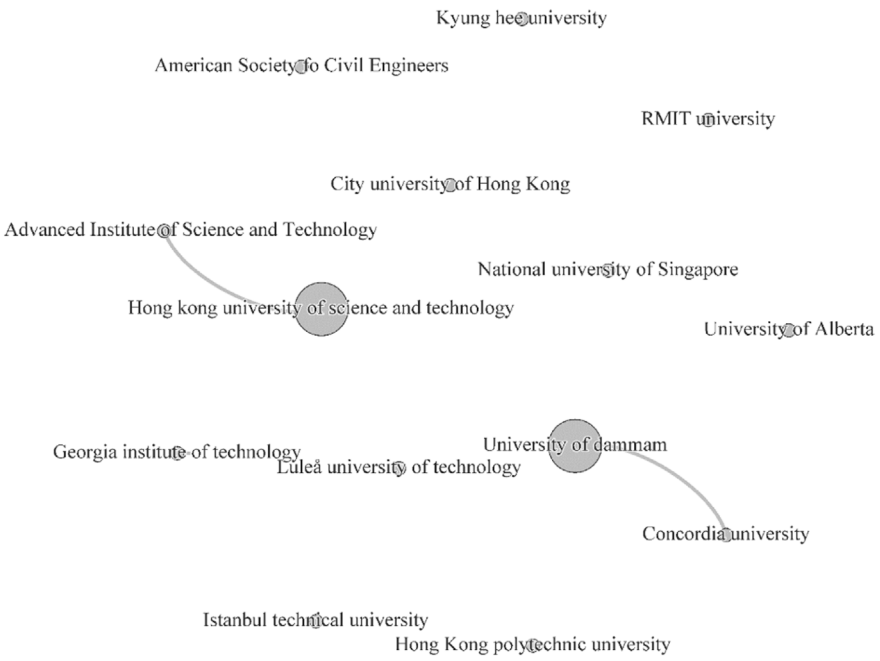

Fig. 6. Collaboration network of institutions in OCR.

prominent institutions involved in the network was not observed in the network in Fig. 5, reflecting the isolated nature of research in these active institutions, which is an indication of lack of knowledge exchange among investigators in active institutions, another problem identified with the current literature in OCR.

4.4.3. Influential countries

To identify the most influential countries and to map the collaboration between them, a collaboration network was created according to the procedure described in Appendix A. The average degree values were utilized to identify the most influential countries within this network, as illustrated in Fig. 7. Nodes were resized and recolored based on their degree values, with larger nodes and lighter colors showing higher degree values. As described below, this network reveals findings that are worth noting.

The US and the UK stand out as the most influential countries within this collaboration network in OCR where the US turned out to be the biggest contributor to OCR [3]. Interestingly, the link between these two countries is not strong. Hence, institutions in such pioneering countries need to redefine policies in order to promote collaboration with each other, as a strategy to enhance the overall level of the knowledge in OCR.

XII. In terms of the strength of links, the strongest links were between the paired countries, US-Israel, US-Canada, Australia–Hong Kong, and US–Turkey; however, compared to the possible links in the

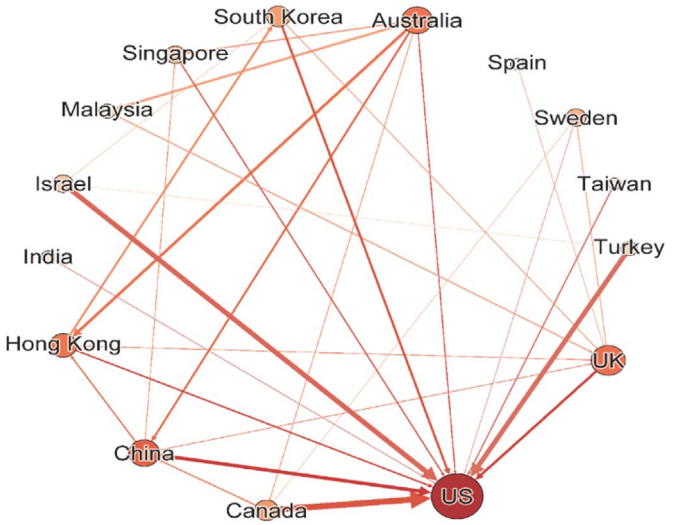

Fig. 7. Collaboration network of countries in off-site construction research (circular configuration for the sake of visibility).

network, the existing links have remained very limited. One consequent gap could be the absence of cross-case and comparative studies within the existing body of OCR to validate theories and findings in different settings.

XIII. Many countries included in the network had weak collaboration links to the main streams of OCR and other members of the network. This needs to be taken into account by these countries adjusting their research policies, as they are positioned far from the dominant network of collaboration in OCR (Fig. 7).

XIV. Developing countries were under-represented in the network. Given that many barriers to the widespread adoption of off-site construction emanate from a lack of knowledge and understanding in these countries [23], this isolation from the main clusters of knowledge in OCR is very detrimental to the off-site construction adoption trend in these countries. This is also a serious impediment towards global trend of off-site construction adoption, compared against the scale of the construction industry in countries such as China and Turkey [3].

5. Discussion of the findings

This study uses Scientometric analysis in order to review the large literature data-set on off-site construction research. It extends earlier review work of this field by complementing existing subjective critical and integral studies with a strong quantitative approach delivered through science mapping tools.

Published studies in the field begin in the mid 1970's, but it is only in the early years of this century that publications in the double figures per year are seen. Indeed, through the second decade, publication numbers rise dramatically with a high of 62 reached in 2014. This trend confirms the sustained growing interest in research in the area.

Limitations in this body of knowledge become apparent, however, when analyzed for content (see Table 2). Product focused themes, such as precast concrete, prefabrication and production planning predominate. Contrariwise, operational and management themes are noticeably neglected, while strategic niches, such as industrial buildings are largely absent. This highlights the incomplete nature of current research as being heavily biased towards the practicalities of component manufacturing concerns. Significantly, this approach leaves the longer-range issues of the future directions and industry adaptations needed to promote sustained development and integration of off-site construction into industry mainstream, untouched.

A further fragility in the current body of knowledge is manifested in the pattern of citations. Citations are a proxy for measuring the cross-fertilization and integration of specific knowledge areas across the whole field. While some ten sub-fields within off-site construction research can be identified, none - not one - can be shown to have any significant impact on the others. The inference to be drawn is that the area is fragmented into 'theme silos,' with no conversation occurring between research themes.

The story with regard to the publication outlets in which research on off-site construction is published, is more complex (see Table 4). An obvious measure of a journals worth as a source of knowledge, is the number of studies in the field any particular journal publishes. In this respect, the Journal of Construction Engineering and Management (JCEM), stands out with by far the largest number of articles on off-site construction, at 91. The journal's strength is diminished, however, when it is realized that it is not the greatest source of citations. By contrast, the Journal of Automation in Construction (AUTOCON), has a fewer 55 articles to its credit, but when weighted for citations, it is discovered to be the greatest source of papers to which other papers make reference. That is, JCEM has published more extensively on the topic, but in doing so, draws its citations from elsewhere, principally from AUTOCON as the more established voice in the field. The lesson here is that academics looking to be cited, or to generate cross-sub-field conversations, would do well to consider where they publish.

This study also considered the relationships between key individual researchers, research institutions fostering research in this domain, and countries of research origin. Mostly, researchers are shown to work in isolation; though two principal research networks can be identified, along with five dyads. The key principal research network centers on the likes of Rafael Sacks, Charles Eastman and Israel Kaner, and their associates. Again, the message here is the value of collaboration with key proponents in the field.

Similarly, too, institutions largely work in isolation, with two exceptions: The Hong Kong University of Science and Technology, and, the University of Dammam. Finally, The US is shown to be the lead country in terms of research influence, along with, perhaps, the UK. In particular, the US harbors research links with more countries than others: Israel, Canada and Turkey; though oddly, less so with the UK.

6. Conclusion

This study explores the current state of research in the field of off-site construction. The area has attracted much interest in the last decade, spawning many studies, and a number of literature reviews have already been undertaken. Nevertheless, this study presents the first bibliometric study of off-site construction literature, in which 501 top-ranked journal articles were systematically examined using a 'science mapping' approach. The findings presented reveal both that much has been achieved, and that much has yet to be done. Principally, this area of study emphasizes 'product' aspects of off-site construction. Moreover, the research work in this area is conducted largely in isolation; this is true whether considered in terms of research themes, the researchers, themselves, or their institutions. The message to be drawn out is that future work in the area of off-site construction would do well to bring in operational, management and strategic considerations into alignment with the current dominant product themes, and to extend collaborations to other parties in order to enhance dialogue, debate and cross-fermentation of ideas and initiatives. Certainly, the enhanced understanding brought about by this study as to the areas neglected in off-site construction research may cultivate industry support for deeper, more carefully focused, research into the field; aiding research planning and funding efforts by policy-makers and practitioners.

Despite the contributions offered in this study, the findings are to be considered in light of several limitations. First, as discussed, the findings are circumscribed by the terms of coverage used in the included literature, their search keywords, along with the omission of conference proceedings and non-English studies. Moreover, given the objectives of

the study, delving beyond the findings into aspects of "why" and "how" research into OCR is conducted as it is, remains beyond the scope of this investigation. Therefore, while several problems within the OCR domain are identified, penetrating these problems to their source and pursuing remedial solutions, remain areas left to be addressed in future research. Additionally, conducting similar studies at future junctures will continue to reveal the evolving nature of literature in OCR, and monitor its on-going integrity and development.

Appendix A. Details of techniques

Technique	Section on the manuscript	Related table/ figure	Computing tool	Description	Reference
Co-occurrence of keywords	4.2.1	Fig. 2 Table 2	VOSviewer Gephi	Author keywords were used instead of all keywords to present a reproducible visualization of the keywords. Fractional counting was deployed and 1348 keywords were extracted from the dataset. With the minimum number of occurrences set to default value of 5, 45 terms, connected through 147 links, were found to meet the criteria for inclusion in the network.	van Eck and Waltman, 2014; Cherven, 2015 [70,69]
Document co-citations	4.2.2	Fig. 3 Table 3	VOSviewer Gephi	The data were submitted to VOSviewer. Type of analysis was set to 'Co-citation', unit of analysis to 'Cited references', and the Counting method to 'Fractional counting'. VOSviewer extracted information from 10164 distinct references for creation of the network. With minimum number of citation of a cited reference was the default value proposed by VOSviewer, 3, 68 nodes with 315 links met the threshold.	van Eck and Waltman, 2014; Cherven, 2015; Chen et al., 2010 [68–70]
			CiteSpace	Clustering function was used and the labels for clusters were created using the LLR algorithm with indexing terms. 43 clusters were identified which reduced to after using the "filter out small clusters" function. *Network signature:* *Timespan: 2003-2017* *Selection criteria: Top 50 per slice* *Network: N = 349, E = 1053 (Density = 0.0173)* *Nodes Labeled: 5.0%* *Pruning: None* *Modularity Q = 0.9104* *Mean Silhouette = 0.431*	
Direct citation analysis of outlets	4.3	Fig. 4 Table 4	VOSviewer Gephi	The data were submitted to VOSviewer with "direct citation" as the type of analysis and "sources" as the unit of analysis. Minimum number of documents in a source and minimum number of citations of a source were set to 10 and 10, respectively. Out of the 26 sources identified, 12 outlets met the set criteria and were included within the resultant network. Removing similar outlets yielded a network comprised of 12 outlets connected via 34 links.	van Eck and Waltman, 2014; Cherven, 2015 [70,69]
Co-authorship analysis of documents	4.4.1	Fig. 5	VOSviewer Gephi	The data were submitted to VOSviewer with type of analysis set to "co-authorship", unit of analysis being "authors" and the counting method set to "fractional counting". Of the 908 identified authors, 12 met the criteria of the minimum publications by an author. This was a minimum of 3 documents and 30 citations for an author (to create a readable and manageable network). With these criteria applied, 29 authors were found to be linked in 8 clusters through 5 links.	van Eck and Waltman, 2014; Cherven, 2015 [70,69]
	4.4.2	Fig. 6		The data were submitted to VOSviewer with the type of analysis as "co-authorship", unit of analysis being "organizations" and the counting method set to "fractional counting". The minimum required number of documents of an organization for inclusion in the network were set to 2 and minimum number of citations to 10. Out of 756 organizations within the dataset, 18 met these criteria to be included in the network.	
	4.4.3	Fig. 7		Data were submitted to VOSviewer with the type of analysis as "co-authorship", unit of analysis being "countries" and the counting method set to "fractional counting". The minimum	

number of documents and citations of a country were set to 10 and 15, respectively. Out of 51 countries organizations within the dataset, 15 met these criteria to be included in the network. The resultant network (15 nodes connected through 30 links) was submitted to Gephi for visualization.

Appendix B. List of top-ranked construction management journals (alphabetic order)

1. Architectural Engineering and Design Management
2. Automation in Construction
3. Building and Environment
4. Building Research and Information
5. Canadian Journal of Civil Engineering
6. Construction Economics and Building
7. Construction Innovation: Information, Process, Management
8. Construction Management and Economics
9. Energy and Building
10. Engineering and construction management
11. Engineering, Construction and Architectural Management
12. Facilities
13. Habitat International
14. International Journal of Construction Education and Research
15. International Journal of Construction Management
16. International Journal of Project Management
17. Journal of Architectural Engineering
18. Journal of Civil Engineering And Management
19. Journal of Computing in Civil Engineering
20. Journal of Management in Engineering
21. Journal of Performance of Constructed Facilities
22. Journal of Professional Issues in Engineering Education and Practices

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