SUSTAINABILITY OF OFF-SITE CONSTRUCTION: A BIBLIOMETRIC REVIEW AND VISUALIZED ANALYSIS OF TRENDING TOPICS AND THEMES

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ABSTRACT

Off-site construction (OSC) involves the fabrication and assembly of building components in a purpose-built factory which are then transported to the job site for final installation. OSC has proven to be a greener construction approach, spurring research towards benchmarking the sustainable attributes of the technique. However, a quantitative statistical analysis of studies on OSC sustainability and a framework of the knowledge domain are not well-established. Drawing on 642 bibliographic records from Scopus, this paper conducted a bibliometric and visualized analysis of research on the sustainability of OSC from 1971 to 2019. The findings show that research publications on OSC sustainability only witnessed steady growth since 2000. A geospatial analysis revealed that at least 32% of countries are involved in the OSC sustainability research, of which the United States, China, Australia, the United Kingdom, and Canada make the greatest contributions. The hot topics in the contemporary OSC sustainability research were identified as embodied carbon, embodied energy, construction waste, post-occupancy evaluation, resources conservation, and recycling, and cost savings. The paper identified areas that require further research. Thus, the paper offers an all-embracing understanding of the core research themes, trends, and patterns on OSC sustainability to stakeholders.

KEYWORDS

bibliometric, bibliographic, off-site construction, sustainability

1. INTRODUCTION

The construction sector constitutes a significant booster of economic development and critical machinery for coping with infrastructure demand and rapid urbanization. However, the business model of the conventional cast-in-situ construction (CCC) approach is largely in conflict with the core principles of sustainability and sustainable development (Axelsson et al. 2011). The International Energy Agency (2019) found that buildings and construction activities

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account for about 36–40% of global final energy consumption. This figure is profound considering the annual energy consumption rate of about 8.92 x 10^9 metric tonnes equivalent of oil energy consumption and the projected annual rate of about 14 x 10^9 metric tonnes equivalent of oil by 2020 (Allouhi et al. 2015). The construction sector is also responsible for over 55% of total global electricity demand (International Energy Agency 2019). Again, the construction sector is one of the profound contributors to climate change due to the emission of 30–40% energy-related total carbon dioxide emissions (Global Alliance for Buildings and Construction 2018; Intergovernmental Panel on Climate Change 2007). The delivery method of the CCC also generates excessive noise, community disturbance and exposes construction workers to safety and risks of work-related musculoskeletal disorders (Bureau of Labor Statistics 2017). Egan (1998) further reported that global CCC is associated with profound lifecycle costs, less productivity, project delays, and cost overruns.

All these attributes underscore the unsustainable attributes of the CCC in the construction industry as they are in direct conflict with environmental, economic and social sustainability tenets. Expectedly, the construction sector is under the increasing requirement to adopt sustainable business models (Kibert 2007). Within the sustainable construction paradigm, green building and offsite construction (OSC) are prominent initiatives (Egan 1998; Kibert 1994). OSC draws on manufacturing business models where 90% of a whole building can be completed in an offsite construction factory (Smith 2016). OSC constitutes a construction process where major components of a project are engineered and produced in an off-site location and then finally transported to a job site for final assembly and installation to generate a complete building (Construction Industry Council 2018). OSC has proven to be a cleaner and more sustainable construction approach (Chen et al. 2010a; Faludi et al. 2012; Jaillon and Poon 2008). For instance, Jaillon et al. (2009) found that OSC techniques reduced about 52% of the construction waste in Hong Kong. The Waste & Resources Action Programme (2007a) noted that a large scale application of OSC would result in the reduction of 70–90% of total wastage in the UK's construction sector. Also, off-site fabricated components are now increasingly being manufactured from recyclable materials; thus, modular homes are considered recyclable (Waste & Resources Action Programme 2007a). Owing to the use of energy-efficient systems and reductions in the total number of deliveries to construction sites, OSC resulted in a 67% reduction in energy usage in the UK (Waste & Resources Action Programme 2007a). Similarly, Mao et al. (2013) found that residential OSC projects had lower emissions of 336 kg/m^2, compared to 368 kg/m^2 in conventional projects in China. Haas and Fagerlund (2002, p. 7–10) further detailed the sustainability benefits of OSC. Furthermore, McGraw Hill Construction (2013) found that OSC resulted in the improved safety and health of construction workers in the UK owing to the controlled factory environment, reduced onsite activities, fewer construction workers on site and the minimized requirement to work from heights. Besides, OSC is flexible and adaptable to the users' changing needs; thus, changes can be effected without demolition and disturbance to the surrounding landscape and neighborhood (Richard 2006; Waste & Resources Action Programme 2007a).

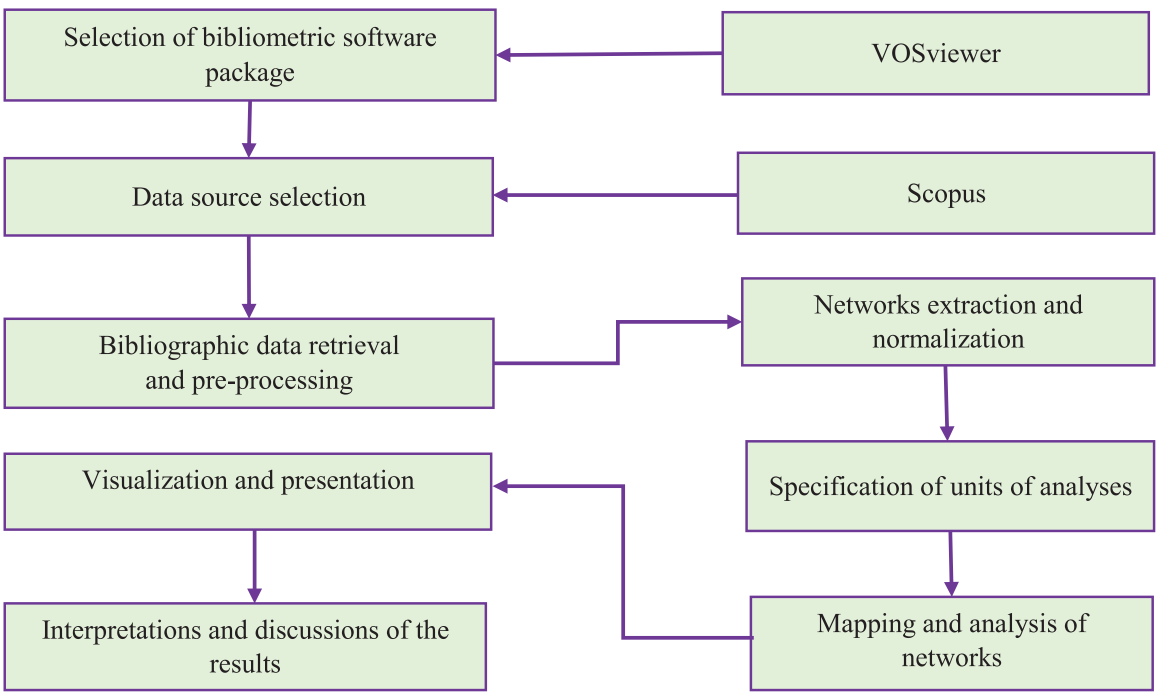
Due to the numerous benefits of OSC, it has received increased attention from both OSC researchers and industry practitioners (Hosseini et al. 2018; Jin et al. 2018). This rising interest came along with a concomitant rise in studies on the sustainability of OSC. The larger universe of studies on the sustainability of OSC engenders obscurity in identifying boundaries of existing knowledge and areas that require further studies. Previous OSC reviews have been generic and offered very little on the research progress of OSC sustainability. For instance, Hosseini et al. (2018) and Jin et al. (2018) both offered scientometric reviews of global research trends on OSC. However, the sustainability of OSC was not well-documented; meanwhile, sustainability constitutes one of the key drivers in the adoption of OSC in the construction industry (Blismas et al. 2006; Blismas and Wakefield 2009; Mao et al. 2018). Because the sustainability of OSC has become topical in the last decade, there is, therefore, the need for critical reflection and in-depth analysis of the extant literature on the sustainability of OSC. This paper conducts a state of the art bibliometric and visualized analysis of studies on the sustainability of OSC. The objectives of this quantitative and visualized analysis of the scientific studies are to (i) examine the annual research publications trends on OSC sustainability, (ii) reveal trends and linkages in salient research areas; (iii) examine the nature of scientific collaborations; (iv) generate a geospatial network of productive OSC sustainability research countries and (v) highlight research gaps in existing studies. Dominant research hot spots and future research directions for OSC sustainability studies will be highlighted. As such, this research has implications for OSC practitioners, researchers, policymakers and research institutions. It will offer useful evidence to strengthen the advocacy for OSC adoption and will also equip stakeholders with a comprehensive understanding of the state-of-the-art research on OSC sustainability.

2. RESEARCH METHODOLOGY

2.1 Rationale for the adoption of bibliometric analysis

The larger universe of published scientific studies on the sustainability of OSC makes it practically inefficient to conduct manual reviews as the results would be influenced by the subjectivity of the reviewers and may lack reproducibility (Markoulli et al. 2017). Manual reviews cannot also analyze for a network of authors, institutions, journals, and countries. These limitations

FIGURE 1. Research approach for the bibliometric and visualized analysis.



of manual qualitative reviews can be effectively addressed using quantitative science mapping techniques to conduct domain analysis and visualization (Cobo et al. 2011).

Cobo et al. (2011) described science mapping as a computational technique of detecting the intellectual structure of a scientific research specialty through domain analysis, visualization and modeling. Hosseini et al. (2018) noted the main science mapping techniques are informatics, bibliometrics, and scientometrics. This paper adopted a bibliometric mapping technique to conduct a quantitative analysis of extant literature on the sustainability of OSC and to describe the knowledge structure and distribution of patterns in the contribution of authors, documents, journals, institutions, and countries. Mayr and Scharnhorst (2015) defined bibliometrics as a quantitative statistical analysis and visualization of published literature. Although scientometric analysis is widely used as a more comprehensive science mapping technique relative to bibliometrics, there are differences that blur the use of the two techniques (Hosseini et al. 2018). Based on the aim of the study, the bibliometric analysis was considered sufficient since it is a powerful quantitative statistical analytical tool that can identify patterns in scientific research outputs, a network of keywords and spatial distribution of authors, documents, and institutions (Cobo et al. 2011; Mayr and Scharnhorst 2015). The paper used a systematic methodological framework comprising the selection of bibliometric software package, data source selection, data retrieval, pre-processing, network extraction, normalization, mapping, analysis, visualization, presentation, interpretation and discussions of the results. FIGURE 1 is a flowchart of the research approach adopted.

2.2 Selection of bibliometrics tool

Owing to the relevance of science (or bibliometric) mapping and its increasing applications in manifold research fields, several tools have been developed to facilitate effective deployment of the technique. Prominent among them are CitNetExplorer, CiteSpace, Gephi, BibExcel, VantagePoint, SciMAT, VOSviewer, etc. (Cobo et al. 2011). Recently, however, CiteSpace and VOSviewer have taken center-stage in science mapping discourses in the construction engineering and management (CEM) research domain (Hosseini et al. 2018). These two science mapping software packages have their unique strengths and weaknesses (van Eck and Waltman 2014). Although both VOSviewer and CiteSpace are visual analytical tools for detecting trends and patterns in the scientific literature (Cobo et al. 2011), the former is used in the current study for four reasons. First, VOSviewer (version 1.6.9) is an open source tool with less obscurity in its installation and usage. Second, van Eck and Waltman (2010) highlighted that VOSviewer is bespoke text-mining tools designed to visualize and analyze bibliometric networks. Third, VOSviewer has sufficient functionalities for conducting reliable bibliometric and visualized analysis of scientific literature (van Eck and Waltman 2014). Finally, VOSviewer is quite easy to use and tolerate varied formats of bibliographic data from Web of Science, Scopus, Dimensions, Crossref JSON, Crossref API, and PubMed. VOSviewer has been used in previous CEM. For instance, the tool was used to analyze research trends on green buildings (Wuni et al. 2019b), thermal comfort and building control (Park and Nagy 2018), building information modeling (Oraee et al. 2017), etc. Thus, there are best practices to learn in the adoption of VOSviewer in the current study.

2.3 Data source

Bibliographic data from databases constitute the major source of data in bibliometric analysis (van Eck and Waltman 2014). As such, the comprehensiveness and quality of a bibliometric analysis may be influenced by the database adopted. What constitutes a suitable database is both context, subject (field) and software-dependent. However, the sustainability of OSC is situated within the CEM research domain and VOSviewer accepts varied files format. Thus, the context, subject and software combination in the current study provides wider options of databases. For comprehensiveness, the authors examined multiple bibliographic data sources such as Elsevier's Scopus, Clarivate Analytics' Web of Science Core Collection, ASCE library, Engineering Village, Taylor and Francis, and Emerald Insight. Following preliminary searches, Scopus was found to be the most comprehensive in coverage, associated with ease of search restriction and consistent in results retrieval. Indeed, previous scientometric and bibliometric analyses relied on data from Scopus (Hosseini et al. 2018; Wuni et al. 2019b). Scopus is widely used for systematic review of academic literature (Huo and Yu 2017; Wuni et al. 2019b). Following the selection of Scopus, the authors specified the keywords to be included in the search string. It should be recognized that sustainability is complex and difficult to delineate exhaustive boundaries. As such, the most commonly used indicators were adopted to reflect the triple bottom line (Chen et al. 2010b; Jaillon and Poon 2008). Also, all models of OSC were identified in the literature.

The full set of synonyms for sustainability used in the search include: *green, sustainable, sustainability, energy, embodied energy, emergy, embodied carbon, emissions, carbon dioxide, CO2, greenhouse gas, waste, indoor air quality, thermal comfort, insulation, ventilation, climate change, user satisfaction, environment, environmental, pollution, lifecycle, life cycle, ecology, ecological, safety, health, society, investment, profit, value, employment, disturbance, hazard, lean, and agile*. For OSC, the synonyms used in the search include: *offsite construction, off-site construction, offsite production, off-site production, off-site manufacturing, prefabrication, prefabricated, prefab, pre-fabricated, off-site fabrication, industrialized building, modular construction, modular home, modular house, modular integrated construction, modern method of construction, precast construction, prefabricated prefinished volumetric construction, and industrialized construction*. The fuzzy Boolean concatenator 'AND' was used to search for articles containing at least two terms, one from each set of keywords.

Some restrictions were made to narrow the search. For comprehensiveness, no *date range* was specified. The *Document type* was restricted to *Articles* or *Review Articles* and thus, no conference paper was included. This restriction was made because Santos et al. (Santos et al. 2017) described journal research articles as the most influential and verified form of scientific knowledge which is considered sufficient to delineate boundaries of knowledge in a given subject. The *Language* of documents was restricted to *English* as it is the most used scientific language in the world. Since 'modularity' in CEM domain is borrowed from computer engineering and other fields (Baldwin and Clark 2000), the authors found it necessary to restrict the subject areas. Again, the term 'sustainability' is applied in many fields, highlighting the need to restrict the subject area. Following all restrictions, Scopus retrieved 642 documents. The bibliographic data of all these documents were exported into a comma-separated values (CSV) file format. This CSV file was then imported into VOSviewer (version 1.6.9) for the bibliometric analysis and visualization.

2.4 Analytical protocol

Based on units of analyses such as authors, documents, journals, institutions and keywords, Cobo et al. (2011) indicated that multiple science mapping outcomes can be achieved. Prominent among them include co-author analysis, co-word analysis, co-occurrence network, bibliographic coupling, co-citations analysis, network analysis, temporal analysis, burst detection, geospatial analysis, modularity maximization, bootstrap resampling, spectral clustering, and thematic areas visualization. However, considering the objectives of the study, the bibliometric and visualized analysis encompassed annual publications trend analysis, co-occurrence network of keywords analysis, source citation analysis, co-authorship analysis, geospatial network analysis, and document citations network analysis. These were selected to highlight the publications trends on the sustainability of OSC, dominant research areas, most active research outlets, most active researchers, most active countries, and landmark articles, respectively. van Eck and Waltman (2014) argued that these are sufficient to understand the knowledge structure of a scientific field. These analyses mainly involved the generation and visualization of networks and maps.

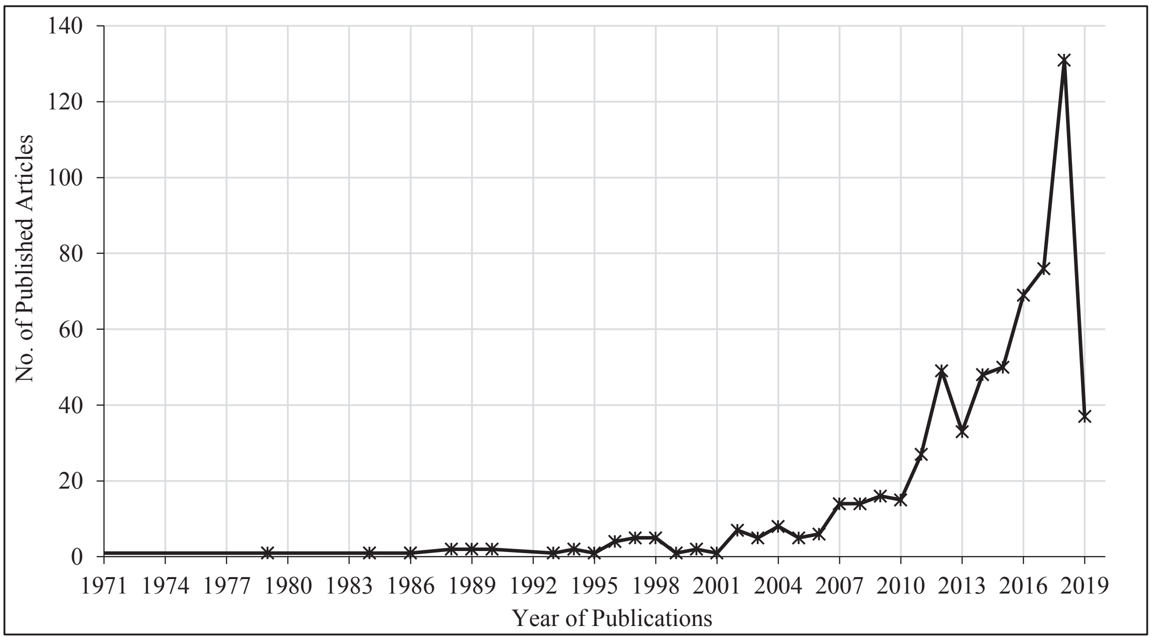
3. BIBLIOMETRIC RESULTS, VISUALIZED ANALYSIS AND DISCUSSIONS

3.1 Analysis of annual research publications trend

The research publications trend for a scientific field highlights the research attention and commitment in broadening the understanding in the domain. FIGURE 2 shows the annual research publications trend on the sustainability of OSC from 1971 to 2019. The total sample is 642 documents comprising 93.6% original research articles and 6.4% review articles. The 48-year range emerged as a natural consequence since there was no restriction on the year of publications. This suggests that OSC sustainability has been recognized during the last five decades. However, two sets of distinct trends can be observed in FIGURE 2.

Within the first three (1971–2001) decades, an annual average of 2 articles was published and the highest within the period was 5 research articles occurring in 1997 and 1998. This highlights the dormancy of OSC sustainability research during the 20th century following the reinvigoration of the approach (Wuni et al. 2019a; Wuni and Shen 2019). The superior contribution in 1990 may be partly due to the formalization of sustainable development agenda

FIGURE 2. Annual publications trend from 1971 to 2019 inclusive.



following the 1997 Brundtland Commission report on 'our common future' (United Nations' World Commission on Environment and Development 1987). In the last two decades, research publications on OSC witnessed a steady growth from 7 articles in 2002 to 131 articles in 2018. For some reason, there was a sharp decrease in articles from 49 articles in 2012 to 33 in 2013 but the trend quickly recovered from 2014 onwards. The trend suggests that OSC sustainability is gaining increased attention in the CEM domain in the 21st century as the built environment continues to adopt sustainable business models (Kibert 2007). The rising trend is moving in tandem with the trend of global research on offsite construction (Hosseini et al. 2018). The trend is likely to be sustained because OSC is gaining increasing attention in the CEM domain owing to its manifold bespoke benefits (Blismas et al. 2006) and the fact that sustainability is becoming a key performance criterion in construction projects (Chen et al. 2010b; Jaillon and Poon 2008).

3.2 Analysis of most influential research outlets and high-impact articles

3.2.1 Journal citations analysis

The 642 OSC sustainability research articles were published in 41 research outlets. TABLE 1 shows the top 10 most productive and influential journals with at least 23 articles and 139 citations on OSC sustainability research. Based on Scopus citations counts, Energy and Buildings (1082) ranked first, followed by Building and Environment (913), and Automation in Construction (793). However, except for Energy and Buildings, the order changes completely when the ranking is done based on the volume of publications. As total citations analysis alone is not effective to identify the most influential research outlets, TABLE 1 includes two other indices for measuring and ranking the impact of journals on the OSC sustainability research

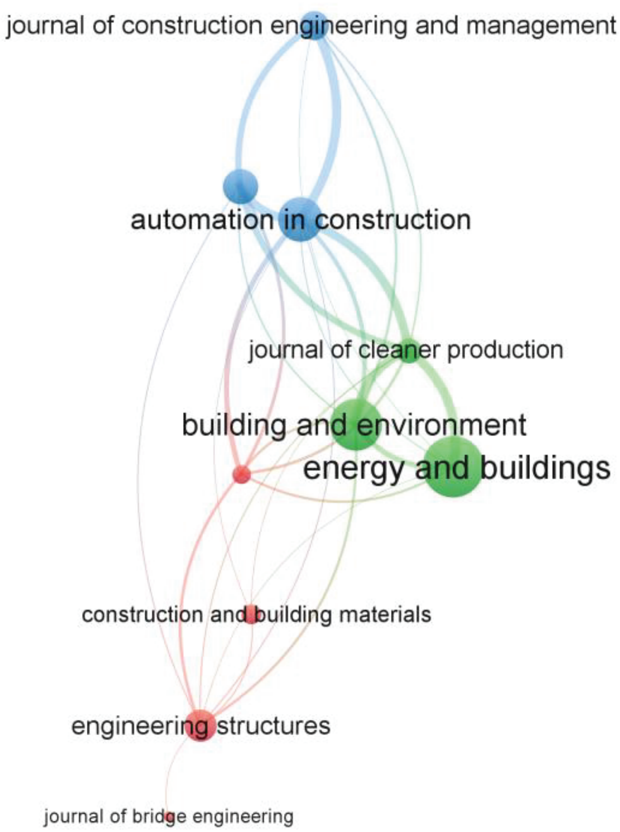
TABLE 1. Numerical statistics of the most influential research outlets.

Research outlet	No. of articles	Citations	Av. Citations	Norm. citations	Total link strength
Energy and Buildings	49	1082	22.08	60.62	48
Building and Environment	23	913	39.70	34.6	65
Automation in Construction	41	793	19.34	59.88	91
Construction Management and Economics	22	630	28.64	19.36	67
Engineering Structures	51	580	11.37	44.96	29
Journal of Construction Engineering and Management	40	527	13.18	32.83	49
Journal of Cleaner Production	34	453	13.32	67.89	92
Construction and Building Materials	35	361	10.31	23.62	11
Journal of Architectural Engineering	25	343	13.72	17.24	48
Journal of Bridge Engineering	23	139	6.04	10.44	2

domain. Average citation measures the influence and impact of each article published in a journal. This gives a fair idea of the quality of the articles in the journals since total citations could be significantly influenced by distinctly higher citations of fewer articles. Under the lens of average citations, Building and Environment (39.70), Construction Management and Economics (28.64), and Energy and Buildings (22.08) published articles with the highest average impact on the OSC sustainability research.

Under the normalized citations index, Journal of Cleaner Productions (67.89), Energy and Buildings (60.62) and Automation in Construction (59.88) contain articles with the greatest standardized impact on the OSC sustainability research. FIGURE 3 shows the co-citation network of the most influential research outlets. The distinctly larger nodes of Energy and Building, Building and Environment, and Automation in Construction highlights their higher impact based on total citations. In FIGURE 3, three clusters of journals can be observed. Each cluster shows the journals that are frequented co-cited by researchers. Energy and Buildings, Building and Environment, and Journal of Cleaner Production belong to the same cluster and the shorter distance between them suggests that they are frequently co-cited by researchers. Journal of Construction Engineering and Management and Automation in Construction also belong to the same cluster (evidenced by color and distance). The third cluster comprises the journals in red nodes. This information provides useful submission information to future researchers and could guide them in Scopus search restrictions.

FIGURE 3. Citations network of the most influential research outlets.



3.2.2 Article citations analysis

Following the principle of the vital few, relatively fewer articles may account for a larger proportion of the total impact of all publications. TABLE 2 shows the top 10 most cited articles on OSC sustainability research. These articles obtained the cumulative impact of 1422 total citations with the first article published in 1997 and the latest published in 2013. In TABLE 2, three impact indices are used to measure and rank the impact of these landmark articles. Based on Scopus total citations, the top 4 most influential articles include the works of Monahan and Powell (2011), Adalberth (1997), Tam et al. (2007), Jaillon et al. (2009), and Chen et al. (2010b). However, since some of the articles were published at different times (year), using

TABLE 2. Numerical statistics of the top 10 high-impact articles.

Authors	Title of article	Scopus citations	Norm. citations	Field-weighted citation impact[a]
Monahan and Powell (2011)	An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework	209	6.54	11.28
Adalberth (1997)	Energy use during the life cycle of single-unit dwellings: Examples	187	3.81	1.87
Tam et al. (2007)	Towards adoption of prefabrication in construction	184	4.67	4.76
Jaillon et al. (2009)	Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong	162	6.22	2.34
Chen et al. (2010b)	Sustainable performance criteria for construction method selection in concrete buildings	150	4.17	6.3
Blismas et al. (2006)	Benefit evaluation for off-site production in construction	121	2.08	8.06
Aye et al. (2012)	Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules	116	4.96	7.04
Jaillon and Poon (2008)	Sustainable construction aspects of using prefabrication in dense urban environment: a Hong Kong case study	111	3.18	3.99
Mao et al. (2013)	Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects	92	4.33	4.51
Goodier and Gibb (2007)	Future opportunities for offsite in the UK	90	2.28	5.11

[a] Shows how well this document is cited when compared to similar documents. A value greater than 1.00 means the document is more cited than expected.

total citations to measure their impact will be misleading. In this case, the normalized citation metric in VOSviewer neutralizes this bias. According to van Eck and Waltman (2019, pp. 37), "the normalized number of citations of a document equals the number of citations of the document divided by the average number of citations of all documents published in the same year and included in the data that is provided to VOSviewer." Effectively, the normalization in VOSviewer eliminates the chances of older articles having more time to receive higher citations than more recent articles. As such, the normalized citation metric is an objective and fair basis to compare the impact of articles published at different times.

Under this index, the top 5 most influential articles include the works of Monahan and Powell (2011) (6.54), Jaillon et al. (2009) (6.22), Aye et al. (2012) (4.96), Tam et al. (2007) (4.67), and Mao et al. (2013) (4.33). However, since the context of the impact analysis is on OSC sustainability research domain, the normalized citation metric also suffers a limitation of not providing a bespoke measure of the influence of these articles within the OSC sustainability research catchment. This is because the articles could be cited in other fields. Thus, the field-weighted citation impact (FWCI) metric provides the true bespoke measure of the influence of these articles on the OSC sustainability research domain. The FWCI is an index in Scopus which measures how well an article is cited when compared to similar articles in a field. A value greater than 1.00 means the document is more cited than expected. From TABLE 2, all ten (10) articles have FWCI values greater than 1, highlighting that they are cited more that than expected based on the publication age. Based on the FWCI scores, the top 3 most influential articles within the OSC sustainability research domain include the works of Monahan and Powell (2011) (11.28), Blismas et al. (2006) (8.06), and Aye et al. (2012) (7.04). It is worth noting that the landmark articles in TABLE 2 examined several critical sustainability issues such as embodied carbon, embodied energy (emergy), greenhouse gas emissions, waste, and sustainability benefits assessment. Thus, this information provides future researchers with highly individualized scientific research information because the cited and citing articles of these documents constitute high-quality literature for bespoke future studies on OSC sustainability. However, TABLE 2 is dominated by articles examining the environmental sustainability aspects of OSC, suggesting that the economic and social pillars are either under-researched or of less concern to researchers.

3.3 Analysis of scientific research collaborations

3.3.1 Authorship network and co-authorship analysis

The collaboration of researchers in scientific studies facilitates knowledge transfers, exchange of ideas, innovation diffusion, and joint grants application. The collaboration mostly involves researchers which translates into institutional, and geospatial partnering research. According to the bibliographic data from Scopus, approximately 1644 authors published the 642 articles on the sustainability of OSC. This translates into 2.56 authors per paper. Generally, this suggests that the collaborative culture of researchers in OSC sustainability studies is relatively low relative to other fields. Chen et al. (2016) found a higher average of 3.45 authors per paper in emergy research. Consistent with research findings in other scientific domains such as emergy (Chen et al. 2016), a group of small prolific researchers makes a significant contribution to the total publications. For instance, the top 35 (2%) most productive authors contributed 231 (36%) of the total publications. TABLE 3 shows the contributions, citations and collaborative links of the 25 most productive authors in the OSC sustainability research studies. Each of the authors in TABLE 3 contributed at least 5 research articles on OSC sustainability and achieved at least 20 Scopus citations.

TABLE 3. Contributions of authors and collaborative links.

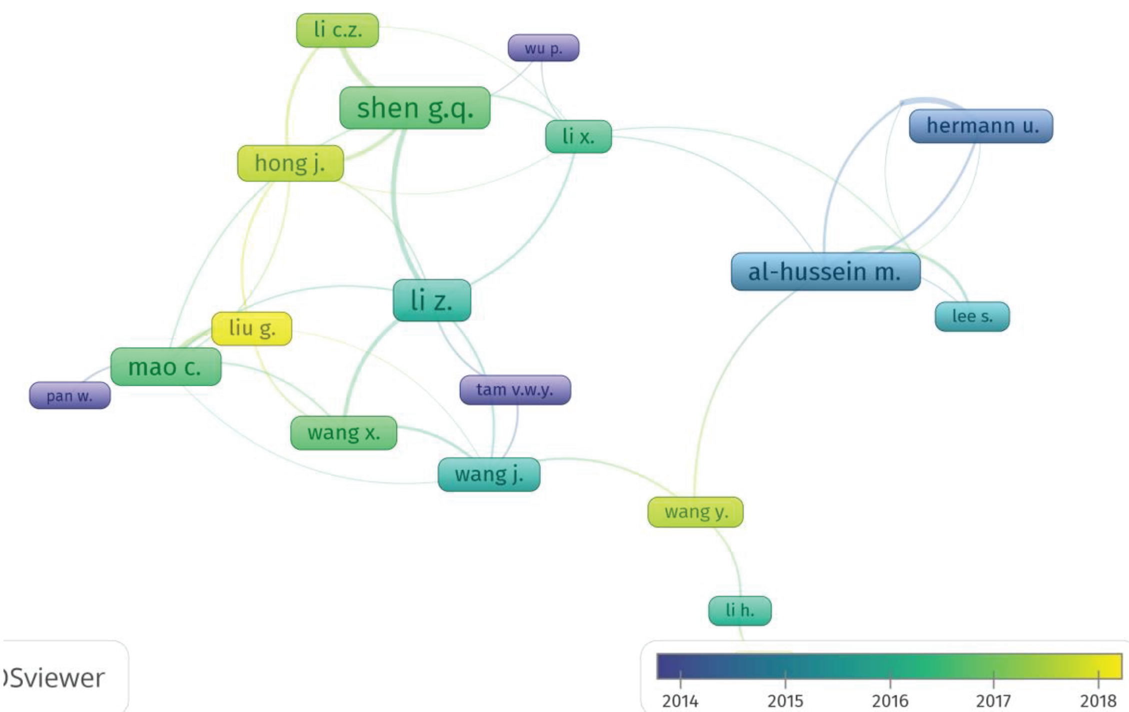
Authors	Articles	Citations	Av. Citation	Total link strength
Al-Hussein M.	16	211	13.19	7
Li Z.	11	295	26.82	9
Mao C.	10	254	25.40	7
Shen G.Q.	10	224	22.40	10
Wang J.	9	191	21.22	5
Li X.	8	85	10.63	4
Arashpour M.	7	81	11.57	4
Lu W.	7	111	15.86	0
Pan W.	7	293	41.86	1
Wang Y.	7	20	2.86	3
Bergado D.T.	6	109	18.17	0
Chen Y.	6	174	29.00	1
Han S.	6	39	6.50	5
Hermann U.	6	92	15.33	5
Hong J.	6	83	13.83	6
Indraratna B.	6	141	23.50	5
Lee S.	6	46	7.67	2
Li H.	6	45	7.50	2
Liu G.	6	24	4.00	5
Liu X.C.	6	68	11.33	5
Poon C.S.	6	390	65.00	4
Tam V.W.Y.	6	311	51.83	2
Wu P.	6	56	9.33	1
Zhang A.L.	6	74	12.33	5
Jaillon L.	5	385	77.00	4

Based on the volume of published articles, the 5 most productive authors include Al-Hussein M. (16), Li Z. (11), Mao C. (10), Shen G.Q. (10), and Wang J. (9). However, the order changes completely when the citation metric is used. In terms of total citations within OSC sustainability, the top 5 most influential authors include Poon C. S. (390), Jaillon L. (385), Tam V.W.Y. (311), Li Z. (295) and Pan W. (293). This order also changes completely when the average citations metric is used. As average citations measure the impact of each published paper of an article, it is more representative than using total citations or number of articles. Under the average citation metric, the 5 most influential researchers include Jaillon L. (77), Poon C. S. (65), Tam V.W.Y. (51.83), Pan W. (41.46), and Chen Y. (29). Thus, Chinese authors represent the most productive and most influential researchers in OSC sustainability research. Aside, Chen Y. whose research focuses on sustainable performance criteria of OSC, the rest of the most influential authors (Jaillon L., Poon C. S., Tam V.W.Y., and Pan W.) focus on the waste reduction potential of prefabricated construction. By tracking the research directions of the authors shown in TABLE 3, future researchers may obtain highly individualized scientific research information. For instance, Mao C. focuses on greenhouse gas emissions and life-cycle energy analysis of OSC projects and Li Z. focuses on waste management and life-cycle energy analysis of OSC projects. Also, Al-Hussein M.'s OSC sustainability research centers on lean application and carbon reduction assessment, and Shen G.Q. focuses on life-cycle energy analysis, greenhouse gas emissions, and waste reduction.

The collaborative landscape and pattern of the authors were also analyzed using co-authorship analysis in VOSviewer. FIGURE 4 shows the collaboration landscape and map of the most productive authors. Since collaboration measures volume rather than impact, FIGURE 4 effectively shows the co-authorship network of the most productive researchers. VOSviewer generates a network, overlay and density visualization using distance-based algorithms. Thus, the size of a node (rectangles or frames) denotes the total contributions and the distance between frames (nodes) measures the collaborative links of authors. Lengthier frames (rectangles) show higher contributions and shorter distances highlight more collaborative links. The total link strength in TABLE 3 "indicates the total strength of the co-authorship links of a given researcher with other researchers" (van Eck and Waltman, 2019, pp. 6).

The combined mapping and clustering of the most productive authors in FIGURE 4 show some useful information. Consistent with column 1 of TABLE 3, the distinctly larger frames (e.g. Al-Hussein M., Li Z., Mao C., Shen G.Q., and Wang J.) are the most productive authors. Although most of the authors have fewer circles of collaborators, FIGURE 4 and TABLE 3

FIGURE 4. Co-authorship network analysis and collaboration landscape of authors.



suggest that the collaborations largely exist among the most productive authors. However, the top 5 most collaborative authors include Shen G. Q. (10), Li Z. (9), Al-Hussein M. (7), Mao C. (7) and Hong J. (7). Based on timelines, the most recent collaborative authors include Liu G., Hong J., Wang Y. and Li C. Z. Apart from Al-Hussein M. and Hermann U., the rest of the collaborative authors are Chinese authors. These intra-regional collaborations are not the best of a collaborative culture and thus, future researchers should foster international collaborations.

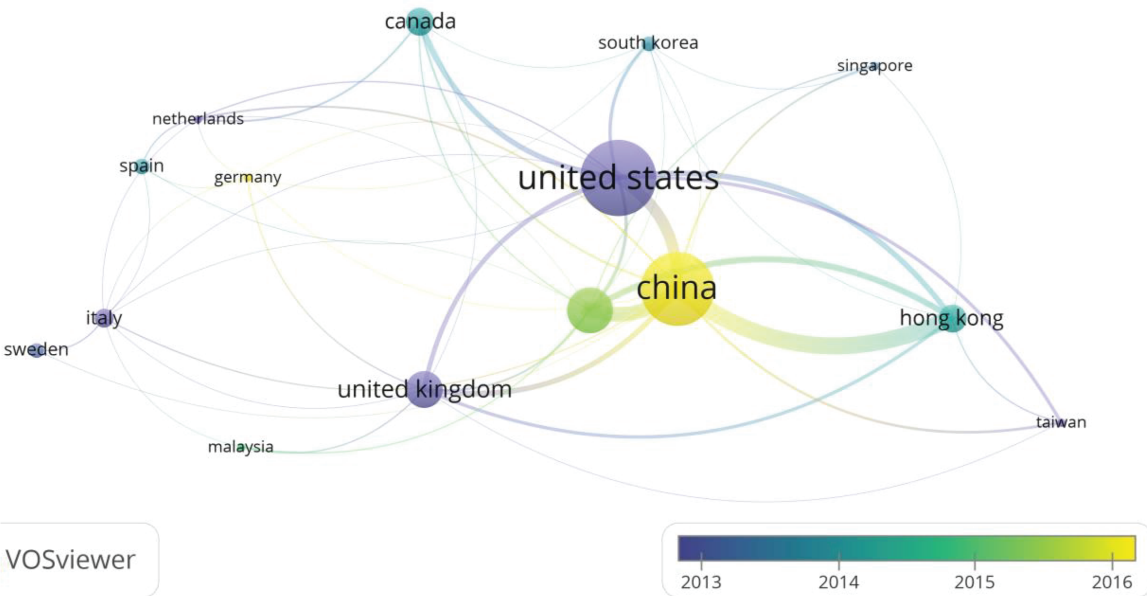
3.3.2 Geospatial distribution and a network of countries

The contribution of different countries to the OSC sustainability research was analyzed in VOSviewer using by specifying 'countries' as the 'unit of analysis' and 'co-authorship' as the type of analysis. This approach estimates the contributions and collaboration of authors based on the location of each author in a paper. As such, this does not indicate the context in which the studies were conducted but rather the geographical affiliations of the authors. The bibliometric analysis shows that at least 62 (32%) of the global 193 or 195 countries are involved in the OSC sustainability research. Of the 62 published territories, the United States ranked first in the volume of contribution (137, 21.34%), followed by China (132, 20.56%), Australia (83, 12.93%), the United Kingdom (66, 10.28%), and Canada (51, 7.94%). The top 15 most productive countries in the OSC sustainability research are shown in TABLE 4 and FIGURE 5 shows their collaborative links. Each of these countries contributed at least 13 articles and

TABLE 4. Most productive countries in OSC sustainability research.

Country	Global Classification	No. of articles	Citations	Av. Citations	Total link strength
United States	Global North	137	1678	12.25	48
China	Global South	132	1645	12.46	69
Australia	Global North	83	1331	16.04	36
United Kingdom	Global North	66	1383	20.95	24
Canada	Global North	51	953	18.69	13
Hong Kong	Global North	50	1516	30.32	37
Italy	Global North	35	604	17.26	8
Spain	Global North	28	463	16.54	3
South Korea	Global North	27	357	13.22	8
Sweden	Global North	27	579	21.44	3
Germany	Global North	14	145	10.36	6
Netherlands	Global North	14	146	10.43	8
Malaysia	Global south	13	259	19.92	5
Singapore	Global North	13	149	11.46	6
Taiwan	Global North	13	106	8.15	7

FIGURE 5. A geospatial network of most productive countries.



achieved over 100 citations. This suggests that the scientific researchers in the institutions of these 15 countries have already paid attention to the sustainability of OSC and published several research findings. Wuni et al. (2019) also found that the United States, China, Australia, United Kingdom, Canada, and Hong Kong constituted the most productive countries in sustainable construction. These countries have some of the most developed sustainability rating tools and they have clear green building policies, OSC sustainability ought to be a critical consideration for their built environment researchers.

As the volume of publications alone cannot objectively measure the research impact of a country, other indices in TABLE 4 offer some useful basis for ranking. Based on total citations, the top 5 most influential territories in the OSC sustainability research include the United States (1678), China (1645), Hong Kong (1516), United Kingdom (1383), and Australia (1331). This order is interesting because the U.S., UK, and Australia did not have authors among the top 5 most productive and most influential researchers. This suggests that the collective contribution and impact of the less productive researchers from these countries is significant. Under the lens of average citations, a different ranking of the countries emerges. Based on average citations, the most influential territories in the OSC sustainability research include Hong Kong (30.32), Sweden (21.44), United Kingdom (20.95), Malaysia (19.92), and Canada (18.69). It can be observed that the United Kingdom is the most productive and influential country under all three indices. Indeed, some of the earlier studies on PPMOF-prefabrication, preassembly, modularization, and offsite fabrication were conducted by British researchers and academics (Gibb 1999; Pan et al. 2008; Tatum et al. 1986).

Typically, British academics such as Tatum, Wakefield, and Gibb are some of the most cited global offsite construction researchers (Hosseini et al. 2018). Based on the global classification, it is conspicuous in TABLE 4 that countries in the global north make higher contributions and impact on OSC sustainability research than those of the global south. Indeed, the only two economies from the global south include China and Malaysia (TABLE 4). On a continental basis, Europe and Asia occupy the top productive position with six countries each within the most contributing continents. South American and African countries contributed the least. The combined mapping and clustering of the most productive authors in FIGURE 5 show some useful information. As VOSviewer generates size and distance-based maps, countries represented by bigger nodes make the most contribution and closely situated countries have a stronger collaborative culture.

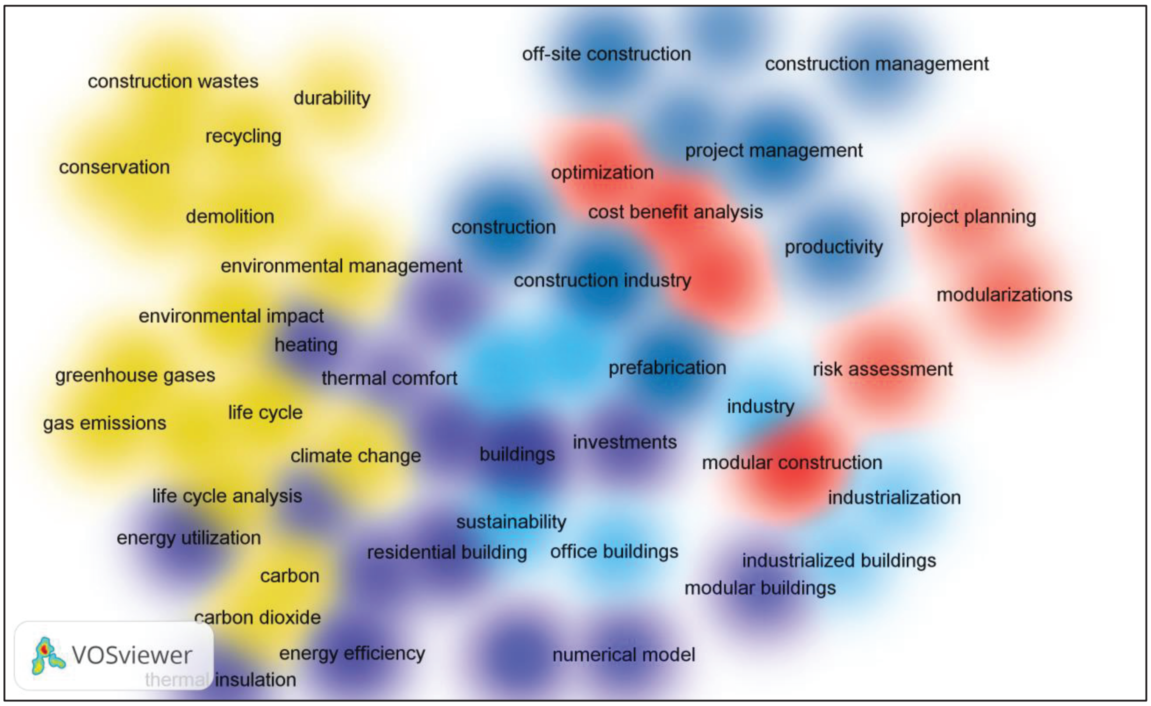
The size of the edges (connection lines) represents the magnitude of collaboration. Based on total link strength (TABLE 4), the top 6 most collaborative countries in OSC sustainability research include China, United States, Hong Kong, Australia, the United Kingdom, and Canada. Within the network (FIGURE 5), the strongest research collaboration exists between researchers in China & Hong Kong, the United States & China, and United Kingdom & China. Essentially, China is the most collaborative country in OSC sustainability research. Countries such as Sweden, Italy, Spain, Germany, and the Netherlands tend to cooperate and collaborate more closely. However, the collaboration appears to be regional (within Europe) and thus, researchers in these countries are encouraged to extend their international collaboration and knowledge exchange to other countries outside Europe.

3.4 Analysis of salient research areas

The author and index keywords often reflect the central themes of published studies (Wuni et al. 2019b). Thus, a comprehensive analysis of the most frequently cited terms may be sufficient to delineate the hottest research frontiers in a given field (Su and Lee 2010). van Eck and Waltman (2014) noted that keywords constitute the pillars of the central research theme within the scholarly literature. Since author and index keywords reflect the most useful information contained in articles, Chen et al. (2016) highlighted that bibliometric analysis could reveal the knowledge structure of a subject through a statistical analysis of the most occurring terms in the extant literature. FIGURE 6 shows a co-occurrence network of the most active terms. These terms occurred at least 35 times in 642 research articles. The co-occurrence network analysis in VOSviewer revealed a total of 16,103 terms (author and index) in the 642 research articles, representing an average of 25 keywords per article. This higher mean score of keywords per article is large enough to reflect the main information in each article. FIGURE 6 shows four dominant clusters of research areas, differentiated by colors. However, a thematic content analysis of the individual terms results in 6 main clusters. The bibliometric analysis revealed that the environmental sustainability pillar dominates the literature. FIGURE 7 shows the existing and proposed future research framework. The future research directions are not entirely knowledge gaps, but they constitute areas that have been under-researched owing to their less visibility in the co-occurrence network of keywords in VOSviewer.

Cluster #1 "Embodied carbon and emissions": the construction sector has been chronicled as one of the seven most detrimental contributors to global warming and climate owing to the higher embodied carbon and greenhouse emissions (Global Alliance for Buildings and Construction 2018; Intergovernmental Panel on Climate Change 2007). However, a notable environmental sustainability attribute of OSC is the lower carbon footprint and reduced emissions (Mao et al. 2013; Quale et al. 2012). This constitutes one of the hottest domains of OSC sustainability research since the construction sector is under the increasing requirement to contribute to climate change mitigation and sustainable development goals (Kibert 2007). Notable keywords within this cluster include greenhouse gases, gas emissions, carbon dioxide, carbon, climate and environmental impact (FIGURE 6). Comparative life cycle assessment

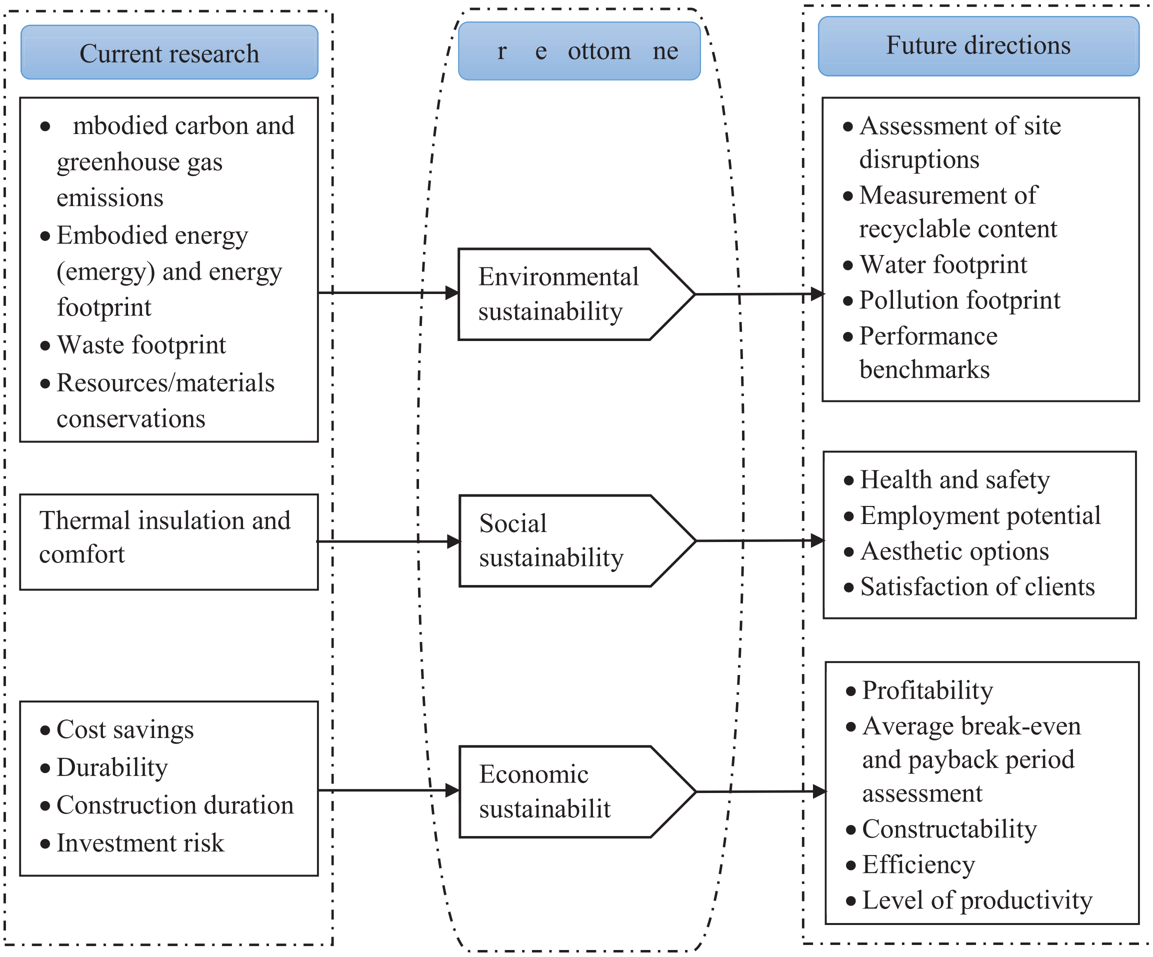
FIGURE 6. Keywords landscape and density map of salient research areas.



(LCA) studies have been conducted to examine the embodied carbon and greenhouse emissions of OSC. A good example is Quale et al. (2012) who found that modular homes have lower life-cycle environmental impact compared to conventional homes. In a partial LCA of a 3 bedroom semi-detached house, Monahan and Powell (2011) found that the application of OSC resulted in a 34% reduction of embodied carbon. Similarly, Aye et al. (2012) found about 54% reduction in greenhouse gas emissions following the use of OSC. These reductions, however trivial, make a profound cumulative impact, in the long run, owing to the larger ecological footprint of the construction sector (Intergovernmental Panel on Climate Change 2007).

Cluster #2 "Embodied energy and consumptions": there is sufficient evidence that buildings and construction consume excessive energy and electricity (Allouhi et al. 2015; International Energy Agency 2019). The projects of OSC are considered cleaner and energy-efficient (Mao et al. 2013). The need to support the green building and energy efficiency initiatives in the built environment spurred research on the energy performance of OSC. Prominent keywords within this research cluster include energy dissipation, energy management, energy efficiency, and energy utilization (FIGURE 6). Studies have found that the application of OSC reduces energy usage in the construction process. The Waste & Resources Action Programme (2007a) found that the use of OSC in housing delivery generated about 67% reduction of energy usage in the UK. On the contrary, Aye et al. (2012) found that the use of OSC in housing delivery in Australia resulted in about a 50% increase in embodied energy. However, the researchers found that the significant potential for reuse of materials in OSC projects may result in about 81% savings in embodied energy. This comparison is could be misleading because both studies were not implemented based on life cycle assessment. Indeed, Adalberth (1997) noted that the management phase of OSC projects in Sweden accounted for the largest (84%) of energy usage and thus, the incomplete assessment may result in misleading comparison.

FIGURE 7. Current and future research directions on OSC sustainability.



Cluster #3 "Construction waste": construction and demolition waste constitute the largest waste footprints in landfills in most countries around the world (Ajayi et al. 2015, 2016). The larger waste footprint of the construction sector is unsustainable because it involves wastage of resources and an increase in the ecological footprint of buildings. For densely populated areas such as Hong Kong, the huge construction and demolition wastes create additional demand on the already scarce land space to be accommodated which has proven to be problematic (Jaillon et al. 2009; Jaillon and Poon 2008; Tam et al. 2007). Indeed, OSC is implemented in Hong Kong to meet housing demand and to reduce construction wastes (Tam et al. 2007). The need to make a sustainable claim for OSC has also spurred research into the waste reduction potentials of OSC. Keyword-indicators of this research frontier includes waste disposal, waste management, construction wastes, and demolition (FIGURE 6). In the UK, the Waste & Resources Action Programme (2007a) found that large scale application of OSC would result in 70–90% reduction in construction waste. In Hong Kong, Jaillon et al. (2009) found a 52% reduction in construction waste following the application of OSC. These constitute a significant contribution to sustainability in the built environment considering the larger ecological footprint of the construction sector and its products around the world.

Cluster #4 "Post-occupancy evaluation": the keywords such as thermal comfort, thermal insulation, heating, quality control, and ventilation are indicators of post-occupancy evaluation research (Altomonte et al. 2017; Hadjri and Crozier 2014). These keywords constitute some useful environmental sustainability indicators (Chen et al. 2010b; Jaillon and Poon 2008). Since these terms are among the top 44 keywords in the OSC sustainability research articles, it means that researchers have gained some interest in understanding the performance of OSC in the context of these parameters. Owing to the urban heat island effect in most cities, there is increasing design requirements to improve thermal comfort, insulation, and natural ventilation in residential construction projects (Altomonte et al. 2017).

Cluster #5 "Resources conservation and recycling": the construction sector is identified as one of the most profound consumers of natural minerals and a large proportion of the world's resources (Ajayi et al. 2016; Intergovernmental Panel on Climate Change 2007). The need to conserve resources throughout the lifecycle of construction projects have been recognized in the OSC sustainability research. Useful keywords under this cluster include 'conservation' and 'recycling'. Common approaches within the OSC business model to conserve resources include the reduction in wastage, improved recycling of construction materials, designing for deconstruction, creating adaptable and intergenerational buildings which can support change without demolitions, and the construction of recyclable modular homes (Richard 2006; Tam et al. 2007; Waste & Resources Action Programme 2007b; a)

Cluster #6 "Cost savings benefits and investment risks": cost overrun has become one of the most detrimental inevitable plagues in the construction industry (Egan 1998). Even time overrun translates directly into the additional cost and the overall cost overrun results in lower profit, lower clients' satisfaction and potential conflicts among project participants. Although higher initial capital requirement constitutes one of the most documented barriers to the adoption of OSC, cost savings also represent a widely documented driver and benefit of OSC (Blismas et al. 2006; Pan and Sidwell 2011). Keywords such as risk assessment, costs, investments, productivity, and cost-benefit analysis (FIGURE 6) suggest that researchers have recognized the need to verify the economic sustainability of OSC. In a comparative study of pre-cast concrete cross-wall panel, timber frame, steel frame, and in-situ reinforced concrete (RC) frame, Pan and Sidwell (2011) found that the first two prefabricated options resulted in 11–32% cost savings. In another comparative study in the United States, Samani et al. (2017) found that prefabricated composite building generated higher life-cycle costs in three different cities compared to those of the masonry building. Conversely, Khalili and Chua (2014) reported a 13% reduction in the cost of OSC projects. These varying findings abound in the literature and complicate the generalization of the cost-saving benefits and benchmarks of OSC. However, Pan and Sidwell (2011) noted that the proper selection of construction materials and optimization of the construction delivery process will eventually result in high-cost savings in OSC.

4. CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

This study investigated the trending topics and research themes on the sustainability of OSC. Drawing on a bibliographic data of 642 research articles from Scopus, this paper conducted a bibliometric and visualized analysis of the OSC sustainability research frontiers from 1971 to 2019. The analysis involved quantitative statistical analysis and visualization to explore the OSC sustainability knowledge structure. The publications trend analysis shows a steady growth of bibliometric records on OSC sustainability research, starting from the year 2000. This shows that the sustainability of OSC has already gained the attention of researchers who have published research findings.

It also demonstrates the flourishing commitment to the promotion of OSC. Of 1644 authors, Al-Hussein M., Li Z., Mao C., Shen G.Q., and Wang J. occupy the top 5 most productive researchers. In terms of total Scopus citations, Poon C. S., Jaillon L., Tam V.W.Y., Li Z., and Pan W. are the most influential researchers within the OSC sustainability research. The analysis also shows that the top 5 most collaborative authors include Shen G. Q., Li Z., Al-Hussein M., Mao C. and Hong J. The paper highlighted the research focus of these academic citizens, and thus, offers future researchers with highly individualized scientific research information. In terms of geospatial distributions of the bibliometric record of 62 countries, some findings emerged. The top 5 most productive countries include the United States, China, Australia, the United Kingdom, and Canada. However, the United States, China, Hong Kong, United Kingdom, and Australia are the most influential countries based on citations. This highlights the flourishing and increasing sustainability visions of these countries in the construction sector. China emerged to be the powerhouse of scientific research cooperation. The country had collaborations with nearly all the 62 countries, highlighting the collaborative ambition and vision of the country. The analysis further revealed that the global North makes higher contribution and impact than the global South. On a continental basis, researchers from Europe and Asia made the greatest contribution and impact.

The most influential and high-impact journals on the OSC sustainability research include Energy and Building, Building and Environment, Automation in Construction, Construction Management and Economics, and Engineering Structures. These research outlets have published significant findings on the sustainability of OSC and obtained citations between 580 and 1082. The document-citations analysis revealed that Monahan and Powell (2011), Adalberth (1997), Tam et al. (2007), Jaillon et al. (2009), and Chen et al. (2010b) are the five most cited articles. However, based on the Field-weighted citation impact, Monahan and Powell (2011), Blismas et al. (2006), and Aye et al. (2012) constituted the three most influential articles within the OSC sustainability research frontiers. Meanwhile, the top 10 most cited articles examined critical sustainability issues such as embodied carbon, embodied energy (emergy), greenhouse gas emissions, waste, and sustainability benefits assessment. Hence, the articles constituted useful reference literature for future researchers.

The paper analyzed the co-occurrence network of keywords to identify salient research areas. Of 16,103 terms, 44 were cited at least 35 times. Through a density map, the paper identified six clusters of hot-topics in the OSC sustainability research comprising *embodied carbon and greenhouse gas emissions, embodied energy and consumptions, construction wastes, post-occupancy evaluation, resources conservation, and recycling, and cost savings*. It is found that existing studies focused more on the environmental aspect of OSC sustainability, resulting in scant research on the social and economic sustainability pillars. The prioritization of the environmental pillar in solitude is constraining the possibility of making a defensible sustainability case for OSC. In response, the paper identified areas that are under-researched within the triple bottom line towards generating more findings on the sustainability of OSC. Under environmental sustainability, future studies may focus on the impact of OSC on-site disruptions, water and pollution footprint, and the establishment of benchmarks for the highly researched indicators. Under social sustainability, future studies may focus on demonstrating the health and safety benefits associated with OSC, aesthetic options and the satisfaction of clients with OSC projects. In terms of economic sustainability, more research is required to accurately measure the profitability of OSC, the average break-even and payback period of investment, constructability benefits, efficiency improvement and the level of increased productivity.

Thus, this paper has useful implications for several stakeholders. Firstly, the quantitative assessment has mapped the knowledge structure of the OSC sustainability research which may be useful to OSC researchers, practitioners, corporate bodies and governmental organizations. The analyses have revealed the publications trend, prominent academic citizens, territories, salient research topics and directions for a future researcher. Secondly, policymakers and corporate bodies may refer to the highlighted collaboration profiles to improve partnering with the key researchers and countries. Thirdly, early-stage researchers may refer to the documented deficiencies and gaps in existing studies to conduct further extensive and rigorous research. Fourthly, domain academics may easily identify the most influential OSC academic citizens with similar specializations and establish collaboration with them in international joint funding applications. Finally, the construction industry practitioners may refer to these findings in the promotion of OSC. Despite the contributions of the study, the following limitations are worth highlighting: (i) the paper used a limited number of sustainability indicators in the Scopus search and thus it is possible that some relevant sustainability issues are not captured in the study, (ii) the use of metrics such as frequency, citations, normalized citations and contributions to rank authors, journals, and regions is quite debatable, and (iii) the salient research areas were developed based on a limited set of the most cited terms and as such, other prominent research areas may have been missed owing to the smaller sample of keywords. Thus, the findings of the study should be interpreted considering these limitations.

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