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Establishing underpinning Metrics for integrating Circular Economy and Offsite Construction: A Bibliometric review

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- Purpose

Circular economy (CE) and Offsite Construction (OSC) are two innovations for improving the construction industry's overall performance against a myriad of sustainability-driven agenda/initiatives. There is a real opportunity to conjoin OSC and CE to provide new insight and opportunities to deliver more evidence-based sustainable systems. This study analyses extant literature in CE and OSC (between 2000 and 2021) through a bibliometric review to tease out critical measures for their integration and transformation.

- Design/methodology/approach

This study adopts a science mapping quantitative literature review approach employing bibliometric and visualization techniques to systematically investigate data. The Web of Science database was used to collect data and the VOSviewer software to analyse the data collected to determine strengths, weights, clusters, and research trends in OSC and CE.

- Findings

Important findings emerging from the study include extensive focus on Sustainability, waste, life cycle assessment and Building information modelling (BIM) which currently serve as strong interlinks to integrate OSC and CE. Circular business models, deconstruction, and supply chain management are emerging areas with strong links for integrating CE and OSC. These emerging areas influence organisational and operational decisions towards sustainable value creation hence requiring more future empirical investigations.

Originality

This study is novel research using bibliometric analysis to unpick underpinning conduits for integrating CE and OSC providing a blueprint for circular offsite construction future research and practice. It provides the needed awareness to develop viable strategies for integrating CE in OSC creating opportunities to transition to more sustainable systems in the construction sector.

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1.0 Introduction

The Construction sector is a crucial sector with significant impacts on the economy and the environment yet, considered the highest consumer of resources and contributor to waste (Zuo and Zhao, 2014; Norouzi *et al*, 2021). Increasing demand for the construction industry to transition to more sustainable systems (Markard and James, 2012; Pomponi and Moncaster, 2017) has emerged innovative solutions such as offsite construction and circular economy (CE) (Li *et al*., 2014; Norouzi *et al*., 2021).

OSC is described as a process involving planning, design, fabrication, and assembly of building elements at a factory to support the rapid and efficient construction of a permanent structure (Smith and Quale, 2017). The claimed benefits of OSC are extensive such as: (i) reduced project duration; (ii) improved quality;(iii) reduced whole life cycle cost; (iv) improved health and safety (v) waste minimisation (Arif and Egbu 2010; Goulding, and Rahimian, 2019). OSC process leverages the supply chain to create value and products that must be technically and economically durable and allow repeated use to support sustainable development. Thus, OSC implementation can contribute to the social, economic, and environmental performance of construction projects and the industry at large (Goulding, and Rahimian, 2019; Sutrisna *et al*., 2018). It is no wonder that the adoption of OSC has stimulated wide public attention for achieving better project and environmental performance in the construction industry. OSC is identified as having an immense potential for sustainable value creation. Hence, there is a real opportunity to enhance OSC with the underlying CE principles to provide new insight and opportunities to deliver more evidence-based sustainable systems.

CE as described by Kirchherr *et al*., (2017) is an "economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes". Other studies (Akanbi, *et al*., 2018; Benachio *et al*., 2020) described CE as a process aimed at promoting the use of sustainable materials, maximising material recovery, and eradicating waste (through maintaining products, materials, and components for the maximum value of time, performance, and utilisation). CE results from preserving a product's integrity at a higher technical and economic durability, for repeated use through value chains, avoiding contamination and toxicity. (Ellen MacArthur Foundation, 2015; Hopkinson et al.,2018).

CE implementation in the building industry globally is still in its infant stage. Various frameworks such as ReSOLVE and the R-Imperatives frameworks (Tserng *et al*., 2021) have emerged for implementing CE. The R-Imperatives frameworks such as the 3R (reduce, reuse, recycle) and the 5R (rethink, reduce, reuse, repair, recycle) are commonly cited frameworks (Kirchherr *et al*., 2017) applicable to the construction industry. Studies (Kibert, 2007; Geissdoerfer *et al*., 2017; Minunno *et al*., 2018; Rausch *et al*., 2021) espoused that CE implementation in construction should embrace reducing construction waste, reuse of replacement parts, use of by-products, design for adaptability, deconstruction/disassembly, recycling and tracking of components. Hence, Tserng et al. (2021), argument that the 5R framework is more relevant to building construction. However, traditional construction practices pose a crucial challenge to implementing CE in the construction sector considering its underdeveloped closed-loop supply chain. Hence the promotion of OSC as a more practical alternative for achieving a circular construction industry (Minunno *et al*., 2018).

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established clear links are beneficial for promoting CE principles in OSC practices leading to more circular OSC systems. Hence the need to systematically unpick underlining constructs that could enhance CE and OSC integration through research to fill this knowledge gap.

This study analyses extant literature in CE and OSC (between 2000 and 2021) through a bibliometric review to tease out critical measures for their integration and transformation. The objectives are to identify current OSC and CE research trends in literature, (ii) emerging constructs for integrating CE and OSC (iii) near and future research directions. The study findings would benefit the academic community as it contributes to (1) providing valuable directions by examining the bibliometric status of OSC and CE from the existing literature identifying the knowledge areas with links for their integration (2) identifying the critical areas needed to advance OSC and CE integration in future studies and to support practical implementation. Therefore, an understanding of how OSC and CE can be integrated can support the development of bespoke strategies and management measures for promoting Circular OSC practices.

2.0 Method

According to Zupic and Čater (2015), researchers typically use three methods to review literature: (i) qualitative approach of a systematic literature review, (ii) quantitative approach by meta-analysis, and (iii) science mapping (based on the quantitative approach using bibliometric methods). Out of the three methods, the third approach is seen most appropriate for determining the state-of-the-art literature of a research field and is fast becoming more popular in various fields of study (Tavares-Lehmann and Varum, 2021). Science mapping combines classification and visualisation employing bibliometric approaches to explore how disciplines, fields, specialities, and individual publications are connected. It has advantages over traditional literature reviews in that it allows for a more objective and systematic selection and evaluation of scientific research on a certain subject (Cobo *et al*., 2015). Science mapping uses bibliometric methods such as citation analysis that help researchers uncover patterns in the structure and dynamics of scientific study domains. In reviews of scientific literature, using the bibliometric technique improves rigour and reduces researcher bias (Cavalieri, *et al*., 2021). To achieve the study aim and objectives, we employed science mapping using a bibliometric method that follows a three-stage review process- (i) data collection, (ii) analysis and visualization, and (iii) interpretation was adopted for this study like a previous study by Norouzi *et al*. (2021). The interpretation of the findings is presented in sections 3 and 4.

2.1 Data collection

The data collection involves a search query, selection of appropriate database(s), and data screening.

Using the proper search keywords in a bibliometric analysis is a critical success factor. We followed the search keywords for offsite according to Jin *et al*. (2018). They selected keywords in the offsite study after a comprehensive assessment of prior relevant studies on the definition and concepts of offsite and created a list of relevant phrases that are used interchangeably. Also, Camón Luis and Celma (2020) identified CE as a specific term used in several literature review studies. Therefore, a combination of suited search keywords was used, and the full search code is 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 "offsite construction" OR "precast construction" OR "tilt-up construction" OR "off-site manufacturing" OR "prefabrication construction" OR "circular economy and construction"

Secondly, we chose a database with bibliometric data. Currently, popular databases for retrieving papers are Scopus and Web of Science (WoS). WoS was adopted and the WoS Core Collection database was employed to extract and collect the bibliographic data used for the study. WoS like Scopus is a digital bibliographic platform that is widely recognised for high-quality standards and a common tool for performing bibliometric research relating to construction. Liu *et al*. (2021) conducted bibliographic analyses and highlighted WoS was a priority choice for review studies in the prefabricated construction field. Similarly, recent literature review studies (Cavalieri et al., 2021 Suchek *et al*., 2021) in CE research have also used the WoS database. The various combinations of terms "offsite" and "circular economy" as established were searched in the WoS database covering the year 2000-2021.

Thirdly, we adopted a set of inclusion and exclusion criteria (relevance, language, and quality) to screen the retrieved data. Following the search in the WoS core collection, 2,064 publications were returned. Documents from non-relevant construction-related WOS categories such as agriculture, pharmacology etc were excluded. Non-English documents in the relevant subject areas were excluded to prevent translation challenges and reduce problems with ambiguity in fundamental concepts. Only peer-reviewed articles and reviews were included to ensure the quality of the documents used. Subsequently, the authors conducted additional skim reads of the title, abstract, and document selected resulting in the further exclusion of documents not related to construction products such as buildings and roads. Applying the relevance, language and quality criteria led to 823 documents being eliminated through the process, leaving 1241 articles that were used for the analysis.

2.2 Data analysis and visualisation

According to Zupic and Čater (2015) and Mas-Tur *et al*. (2021) commonly used bibliometric methods are:

- Co-occurrence analysis examines the conceptual structure of the knowledge in the field, identifying relevant keywords and themes associated with the main concepts of investigations
- Citation analysis uses citation rates to estimate the influence of documents, authors, journals, or countries,
- Co-citation analysis and bibliometric coupling construct measures of similarity between documents, authors, or journals.

This study employed citation, and co-occurrence analysis. The Visualization of Similarities (VOS) viewer software version 1.6.16 was used to present the bibliographic information analysed. VOSviewer enables mapping, visualisation, and identifying the network structure in a study field (Van Eck and Waltman, 2010). It was adopted over other commonly used software such as Pajek and Citespace because of the easier interpretation, presentation, and visualisation of the maps (Van Eck and Waltman, 2010; Leydesdorff and Nerghes, 2017). The network is made up of distance-based maps, where the distance between two items reflects the strength of their relationship. In general, a shorter length indicates a stronger relationship. The number of occurrences in which the term was found is reflected in the size of the item label. A larger label size means that the corresponding item is found in more publications and different colours represent different groups of items that were clustered by VOSviewer's clustering technique (Perianes-Rodriguez *et al*., 2016; Yin *et al*., 2019).

3.0 Results

The bibliometric and network analysis results presented in tables and networks are reported in this section.

3.1 Citation analysis

Citation analysis was conducted to identify high-impact journals and influential countries in the OSC and CE research over time. The volume of publications and high citations are used to understand the impact and quality of study in a particular field (Wang *et al*. 2020; Wuni *et al*. 2020).

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3.1.1 Countries in OSC and CE research

Employing VOSviewer, the minimum number of citations and publications was set at 10 and 5, respectively. This was done to ensure that only countries actively involved in CE and OSC research are selected. Out of the 81 countries available, only 44 countries that met the threshold were selected and results from the analysis are presented in Figure 1.

Insert Figure 1 here

Ten productive countries are at the fore of CE and OSC research. In particular, the Republic of China, (352 publications and 5934 citations) was found most productive in CE and OSC research fields. It was followed by Australia (175 publications and 2337 citations), the United States of America (147 publications and 2424 citations) and England (140 publications and 2905 citations). Other countries within the top ten include Italy, Spain, South Korea, Malaysia, and Netherlands. Amongst the ten, only China and Malaysia were developing countries. These findings corroborate previous findings in OSC (Jin *et al*., 2018; Hosseini *et al*., 2018) and CE (Norouzi *et al*., 2021) studies. Nevertheless, the results showed that the most recent publications (in yellow) in CE and OSC were from Pakistan, South Africa, Vietnam, and Brazil. This shows that study trends are moving towards developing countries, especially those seeking sustainable improvements in their construction industry, hence requiring more empirical investigations.

3.1.2 Journals in OSC and CE research

The analysis was undertaken to find the outlet where CE and OSC are primarily published. The minimum threshold was set at 5 publications in VOSviewer. It is worth noting that of the 247 sources, 56 met the threshold and results from the analysis are presented in Figure 2.

Insert Figure 2 here

Ten productive and impactful journals are at the fore of CE and OSC research. In particular, the Journal *of Cleaner Production* (173 publications and 3838 citations) was most productive, followed by *Sustainability (*115 publications and 607 citations), *Automation in construction journal* (61 publications and 1361 citations) and *Resources conservation and recycling* (45 publications and 1204 citations). Other outlets within the top ten include Engineering structures, Construction and building materials, Engineering construction and architectural management, Journal of construction engineering and management, Journal of building engineering and Buildings. Sustainability seems to have lower citations considering the number of publications which may have resulted from bias toward full open-access journals (Davis, 2011). Furthermore, citations may not be at par considering the short turnaround time for publication compared with traditional non-full open-access journals. The result further showed that the most recent publications (in Yellow) in CE and OSC were published in Sustainability, Applied sciences, Journal of environmental management, and Journal of building engineering. This shows there are emerging journals now embracing studies in OSC and CE within their publication scope. A review of the aim and scope of these identified top journals suggests an emphasis on information technologies, sustainable development, resource management, and construction life cycle management practices. This is not so far away from the goals of many journals in construction and the built environment. Therefore, journal editors may consider making strategic adjustments to their objectives and promote special issues targeted at OSC and CE research.

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3.2 *Co-occurrence analysis of OSC and CE research*

Keywords are essential in bibliometric analysis. Studies, like Lee and Su (2010) and Eck and Waltman (2014), advocate using author keywords for bibliometric analysis to highlight trends in existing research. Thus, author keywords were chosen for the current study as the foundation for building the co-occurrence maps. Guided by an existing bibliometric literature review (Hosseini *et al.,* 2018) and best practices for visualising research clusters (Yin *et al*., 2019), the minimum number of occurrences of a keyword was set at a threshold of 10. Repeated words (such as 'BIM' and 'Building information') and generic words such as China, case study and literature review were omitted. Of the 3849 keywords, 40 met the threshold used for the analysis. Large nodes and colour presentations in the co-occurrence network and the main relationships were explored to analyse the research hotspots and issues dominating the CE and OSC literature. Co-occurrence analysis was based on publication year and cluster formation.

3.2.1 Co-occurrence of author keywords by publication year

The author's keyword distribution is explored using overlay visualisation. The visualisation reveals that there exist several published OSC and CE papers during the period 2017 to 2021 (see Figure 3). The closer the colour to yellows, the more recent the concept is being explored in literature. In addition, a small node in the network, confirms that the concept is just starting to be explored as an area of concern. The findings show that CE literature has attracted more focus recently than OSC literature. The increase in this trend coincides with the need to minimise waste and promote sustainability objectives. CE, OSC, BIM, and sustainability, represented the central keywords which have interrelationships with other keywords in the network and are dominant concepts in the existing literature. The generic trend, on product aspect (precast concrete,) industrial ecology, lean construction, productivity, and construction management, seems to be winding down possibly due to its saturation. Whereas there appears to be a burst in research associated with strategic, process optimisation, digital technological measures. Construction automation, supply-chain management, project management, waste, life cycle assessment, waste management, resource efficiency and deconstruction are emerging areas since 2019 in OSC and CE research. The yellow nodes such as circular business model, built environment, recycled aggregate, and waste management represent the most recent occurring keywords in OSC and CE research. The bursts in these concepts are possibly due to current demands for technical, and economic performance for promoting CE and OSC adoption and implementation in the Built environment. Surprisingly, the term Circular offsite construction did not appear as a keyword in the existing literature which suggests future areas of investigation for integrating OSC and CE.

Insert Figure 3 here

3.2.2 *Co-occurrence of author keywords by clusters*

The keywords "circular economy" and "offsite construction" had large nodes in the network indicating researchers were more interested in studying these systems and their unique components (Ferasso *et al*., 2020). Five clusters as shown in Figure 4 emerge following the analysis.

Insert Figure 4 here

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Cluster 1: - In red is the largest cluster with 13 keywords. Off-site construction, precast concrete, simulation, lean construction, BIM, project/construction management, productivity, construction automation, supply chain management, seismic performance, finite element analysis and optimisation. This cluster indicated a strong focus on OSC *products, process, and technology*. From a product perspective, extensive OSC studies have focused on Precast concrete, (Yin *et al*., 2019) especially due to structural performances. Findings also demonstrate that OSC projects offer a viable testbed and setting for using new technologies (e.g., BIM construction automation, simulation, and optimisation analysis) and theoretical testing concerns connected to innovation, such as seismic performance and productivity.

Cluster 2: In green with seven keywords. The keywords are circular economy, industrial ecology, material flow analysis, circular business model, urban mining, resource efficiency, and built environment. This cluster is concerned with *circularity* and strongly focuses on efficient strategies for achieving environmental and economic benefits (Nußholz, 2017). Excluding circular economy, industrial ecology and circular business models have stronger links. While the former focus on designing more sustainable industrial systems (Norouzi *et al*., 2021), the latter emphasises organisational contributions to create commercial value capitalising on economic and environmental value embedded in products (Pomponi and Moncaster, 2017). OSC is product-focused hence the need to further explore circular business models.

Cluster 3: In blue held five keywords- waste, life cycle assessment, mechanical properties, recycled aggregate and environmental impact. This cluster reviews concerns associated with *waste generation and environmental impact.* It explores concepts focused on the life cycle assessment of solutions and products to minimise waste and environmental impacts. There is an increasing demand to reduce the overall environmental impact and enhance the benefits of economic activities (Zucaro *et al*., 2016). Impact assessments support decision-making in building design and help to improve the industry's progress towards sustainability (Kamali *et al*., 2016; Ghisellini *et al*., 2018). Therefore, developing tools for assessing the environmental impacts of OSC products and processes should be considered from design, to determine effective materials, design and recycling choices and minimise waste.

Cluster 4: In yellow with three keywords- reuse, recycling, deconstruction. This cluster is concerned with exploring e*nd-of-life strategies. Its* focus is on optimising end-of-life alternative scenarios of a facility thereby strategically identifying and minimising waste yet promoting social and economic benefits. Deconstruction as an end-of-life scenario is an emerging area for integrating CE and OSC. Though recycling is an area within this cluster that has received the most attention and has been identified as driving CE (Ji *et al*., 2018) it is not directly linked to OSC. Material management should consider deconstruction for reuse, and recycling from design. Evaluating materials' reusability from design is critical for determining recoverable materials (Akanbi *et al*., 2018). The reuse of recovered construction components and materials at the end of life of a facility can yield economic and environmental benefits (Ghisellini *et al*., 2018).

Cluster 5: In purple contains two keywords- sustainability and waste management. This cluster focuses on issues surrounding *Sustainability.* Waste management is a strategy for disposing of, reducing, reusing, and preventing waste to improve sustainable practices in the built environment (Hossain *et al.,2019) sustainability* drives the concept of waste management hence their strong link. *In this cluster,* sustainability has very strong links to OSC and CE.

4.0 Discussion and Implications

In this section, the five study fields emerging from the results of the analysis are discussed. The knowledge gaps and future study directions are also highlighted.

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4.1 Sustainability

Sustainability is a driver with strong links for integrating OSC and CE and it's no wonder it attracts a lot of attention from researchers (Hosseini *et al*., 2018; Norouzi *et al*, 2021). Geissdoerfer *et al.* (2017) described sustainability as the balanced and systemic integration of intra and intergenerational economic, social, and environmental performance. The current increasing demands on sustainable practices to reduce any environmental, economic, and social impacts is a top priority for the construction industry (Azhar *et al*., 2011). Fundamentally CE principles, provide a closed-loop material flow in the whole economic system supporting the efficient use of resources and minimising waste and emissions (Ghisellini *et al*., 2016). Similarly, the OSC process is geared toward addressing environmental considerations (Sutrisna *et al*., 2018; Goulding and Rahimian, 2019), structural performance and the capability to foster material reuse and recycling. Both CE and OSC principles foster sustainable economic and environmental benefits in the construction industry, hence sustainability has the potential to drive their integration creating possible networks and collaboration. However, studies have not yet explicitly considered the integration of CE and OSC through the lens of sustainability. Sustainability literature on CE and OSC is fragmented and concentrates on a single dimension rather than a balance between the dimensions. For instance, exploring a CE-based material passport analysis for OSC that tracks and evaluate economic and environmental sustainability is suggested. Evaluating economic and environmental sustainability of recycled materials for OSC. Additionally, the impact of OSC and CE integration from economic and social sustainability perspectives should receive greater focus. For instance, indoor environmental quality of OSC buildings constructed with recycled and reused materials/components on occupant wellbeing. Overall, setting a sustainability-based OSC circularity scale/guideline and capability maturity for firms are recommended. Arguably, such investigations would shed more light on measuring the impact of OSC circularity from social, economic, and environmental sustainability perspectives.

4.2 Waste and environmental impact

Waste is a predominant area with strong links to both OSC and CE in this study. Construction and demolition waste has been extensively discussed in OSC and CE literature. This corroborates previous study findings (Ghisellini *et al*., 2018). According to Durmiseric, (2006), demolition and construction waste contribute to the negative perception the public held about the construction industry. Its relationship with life cycle assessment and environmental impact is shown in this study. Minimising waste is a core principle underpinning OSC and CE. CE opposes a linear make-use-dispose system (Pomponi and Moncaster, 2017) while OSC adopts standardised design and processes aligned to the factory production line where materials are made to fit specifications and any left-over resources are stored and used for future projects. Therefore, OSC modules can be manufactured by integrating CE principles such as reuse which significantly minimises material waste to landfills and negative environmental impact. However, studies have not yet explicitly considered the integration of CE and OSC through the lens of waste. Literature on waste in relation to CE and OSC is fragmented and concentrates on singular impact. Future studies can explore waste rates and CE optimal levels for various OSC systems, a niche that can integrate OSC and CE. Such investigation could shed more light on CE impact in enhancing the technical and economic durability of OSC products, facilitating repeated use, and reducing physical wastes in landfills. Prevention is most preferred in the waste hierarchy and needs to be tried as a strategic plan. A broad evaluation of recycled materials (e.g., from demolished buildings) for OSC buildings can be explored through case studies and simulations to develop a CE-based waste prevention framework for OSC practice.

4.3 Product, process, and technology

BIM is another key area with strong links to both OSC and CE. It is fundamental in supporting efficiency in product, process and technological performances, BIM is well voiced to support collaborative efforts at designing out waste, design for deconstruction and improving life cycle performances of building components and elements for longer use (Obi *et al*., 2021; Akbarieh *et al*., 2020). BIM has been espoused as a strategy for optimal selection of alternative building design elements

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and materials hence a catalyst for salvaging building materials in a circular economy (Akanbi *et al.*, 2020). Studies have investigated BIM for OSC and BIM for CE but not BIM for CE in OSC. Past studies have revealed that the potential economic impact of using OSC can be optimised and sustained by applying CE principles (Hairstans and Duncheva, 2019; Webster, 2017). With the advancement of technology such as BIM, there is the potential for integrating CE with OSC to expedite the modern construction process. For instance, a BIM-based generative design factoring CE principles for OSC projects is a promising area. Also, BIM-enabled CE performance analytics for OSC can support the evaluation of CE performance 3R framework throughout the OSC process design. The rich information in BIM can be leveraged throughout the life cycle of the OSC project to assess how CE principles could be maximised in the process. Relevant data can be extracted and analysed to reveal valuable insights for evaluating the circularity of an OSC design or facility. More research could be directed on the relationships between design parameters of OSC elements and CE principles. This might be useful for project stakeholders in defining best practices and standards for CE-based OSC initiatives. These are promising areas to integrate CE in the OSC sector.

4.4 End-of-life

This study shows that deconstruction is an emerging concept of end-of-life disposal with strong links to OSC and CE. Deconstruction allows the disassembly of building components systematically allowing recycling and reuse (Kanters, 2018), thereby reducing carbon emission and pollution (Gbadamosi *et al.*, 2019). Evaluating deconstructability and materials' reusability from design is identified as critical in the choice of end-of-life actions (Akanbi *et al.*, 2018). Strategies such as design for deconstruction (DFD), design for manufacture and assembly (DFMA) and modularity can support the deconstructability viability of OSC project from planning to the end of life. However, there is limited empirical evidence using CE principles in enhancing deconstruction capabilities of OSC buildings and systems. Thus, there is a need for OSC and CE integrated systems for deconstruction management with capabilities to predict if OSC building components specified are fit for purpose, reusable at the end of their life, and can maintain their value is a future area of research. Circular DFD guidelines for OSC projects are recommended for project teams in the built environment

4.5 Circularity

Integrating circularity in OSC supports materials and components reuse and recycling (Cristescu, 2020; Van den Berg, 2019). OSC is more product-focused situating circular business models at the core of organisational contributions to explore value-embedded products. Circular business models are identified as an emerging concept seen with strong links to both OSC and CE. It is seen as an emerging area for integrating CE and OSC. Circular business models aim to promote firms transitioning and reliance on the use of renewable materials as a sustainable production strategy in the supply chain (Osobajo *et al.*, 2020). Construction organisations and project teams must consider CE in designing and delivering their services and product, including OSC products (Geissdoerfer *et al.*, 2017; Kirchherr *et al.*, 2017; Osobajo *et al.*, 2020; Rausch *et al.*, 2021). To outperform the linear model and promote value for effective integration in OSC, CE business models and product flows must be more cost-effective, provide higher revenues, or enhance capital and resource productivity. The construction sector offers the most significant potential for CE innovation, value retention, and development prospects (Ellen MacArthur Foundation, 2015; Hopkinson et al., 2018). To turn the potential of CE into reality in OSC, a new circular building construction system is required that coordinates and integrates essential players and activities such as building and product design, deconstruction and separation, and high value remanufacture, and marketplace exchange (Ajayabi *et al.*, 2019). It should be noted that the literature highlights the need for circular business models associated with offsite construction. However, research is yet to establish circular business models and processes for OSC. This requires business models that maximise the CE Rethink principle. Therefore, is an important research direction for translating CE principles into the OSC. Such research should bring together essential stakeholders in OSC and ownership on a regional scale (for example, design, financing, production, and maintenance) to capture the potential for CE implementation. Combining economic, and environmental success and

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guaranteeing responsible resource management over the manufacturing and usable life phases suggests that OSC may function within CE. Academics, businesses, and government agencies have created various CE-related measurement tools to track the consequences of the transition to a circular economy (Ferasso *et al.*, 2020). However, the available indicators need to be synthesised for proper implementation and a better understanding of their scopes and purposes within the context of OSC. This suggests the need for further research exploring the efficacy of CE in the OSC and providing insight into the extent to which the principles of CE are applicable in OSC activities.

4.6 *Research gaps and future directions*

Past studies have revealed that the potential economic impact of using OSC can be optimised and sustained integrating CE principles (Webster, 2017; Hairstans and Duncheva, 2019). Findings revealed predominant topics in OSC and CE research, highlighting gaps in the current research which may significantly affect adaptation strategies needed for their integration into practice. Hot topics currently explored in OSC, and CE research include BIM' 'sustainability' 'life cycle assessment' precast concrete and 'waste'. These currently served as strong interlinks for OSC and CE integration and will continue to maintain mainstream positions in future studies corroborating previous research (Jin *et al.*, 2018; Yin *et al.*, 2019; Norouzi *et al.*, 2021). Interestingly, other concepts such as supply chain management, circular business models, deconstruction, project management, and environmental impact are emerging areas in research with links to CE and OSC. These areas focus on economic, process and management-related measures useful at strategic, project and operational levels for integrating OSC and CE in practice.

Surprisingly, results showed that though research in CE has considered recycling, reuse, and resource efficiency, they had no direct link to OSC in current research. Furthermore, there is little or no research on CE principles -reduction and repair, in existing OSC and CE literature related to construction. The network visualisation shows a lack of a direct link between OSC and CE. In addition, it was also surprising not to find the term "circular offsite construction" as a keyword in current research. These suggest a lack of holistic studies on CE and OSC integration and a current gap of non-exploration of CE principles in OSC by researchers. This is a missed opportunity in driving the circularity agenda in OSC systems and the construction sector at large. Nevertheless, it presents potential directions for future investigations.

Based on the study findings as discussed, predominant and emerging concepts that can serve as conduits for OSC and CE integration, and the proposed directions for advancing research and practice are summarised in Table I. Future investigations could pay more attention to the current and emerging concepts in CE and OSC as highlighted.

Insert Table I here

Conclusion

This study conducts a bibliometric review of the extant literature on OSC and CE from 2000–2021 to tease out critical measures for their integration and transformation. In this study, 1241 publications on CE and OSC within the building and construction sector retrieved from WoS were analysed using Bibliometrics and network analysis in VOSviewer.

The demographic maturity levels and increased prevalence are most notably from China, Australia, USA, and UK. Nevertheless, trends in recent OSC and CE research are emerging from developing countries, indicating a surge for sustainable improvements in their construction practices. to enhance CE and OSC research globally, developed and developing countries need to collaborate. The poor collaborative links between OSC and CE researchers across developed and developing countries may

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be one of the reasons contributing to the slow understanding and uptake of circular offsite construction systems in developing economies. Therefore, investments in funding research, Hubs and spoke collaborative networks between developed and developing countries should be encouraged. These can facilitate knowledge exchange and transfer on policies and implementation strategies to promote CE and OSC integration practices.

Five cluster areas were identified including Sustainability, Waste and environmental impact Product, process and technology, End- of- life, and Circularity in the built environment. Within the clusters, the most exploited research areas in OSC and CE are related to BIM' 'sustainability' 'life cycle assessment' precast concrete and 'waste'. These areas currently have strong links to OSC and CE and seeks to optimise performance, reduce waste and the environmental impact throughout a building life cycle. There are emerging concepts and there is the need to expound their links especially circular business models, supply chain management, deconstruction practices with OSC and CE. This is with the view of foreseeing a more strategic approach that can deliver a balance of economic, social, and environmental impacts through evaluations of more circular offsite construction practices. Surprisingly, CE principles -recycling and reuse lacked direct links to OSC in current research. This shows a lack of OSC and CE integrated studies in current research. The non-integration of CE and OSC is one of the reasons for the lack of reuse of OSC components. Thus, a missed opportunity for driving the circularity agenda in both OSC systems and the construction sector. These are future research directions towards a circular offsite construction system in practice.

Findings from future research and collaborations can be published in top OSC and CE outlets such as the Journal of Cleaner Production, Sustainability, Automation in construction and Resources conservation and recycling. Nevertheless, there are emerging journals outlets embracing studies in OSC and CE fields. To further expand dissemination of knowledge on CE and OSC practice, there is need for editors of construction-related journals to make strategic adjustments to their objectives. This may include promoting special issues targeted at OSC and CE research to establish relevance in the area and expand their reach.

This study contributed by highlighting the bibliometric status of OSC and CE research, identified current gaps in the literature and provided directions for future studies and practice. More importantly, the evidence gleaned from this study would help OSC players and policymakers, to develop bespoke strategies, frameworks, and policy measures for integrating and implementing CE and OSC practices creating opportunities to transition to more sustainable systems in the construction sector industry. However, there were some limitations. One is the use of the only web of science database. Secondly, the use of only peer-reviewed articles written in English and thirdly exclusion in discussing other emerging areas because they had no current links to OSC and CE. Future studies may employ other databases or combine various sources for improved generalisability. Also, expanding the sources of documents such as books, and conference proceedings including those in other languages to extend the range of data. Future studies may investigate other emerging areas where are currently no links to OSC and CE. In addition, expert systems and fuzzy tools can be used to explore more in-depth quantitative analysis.

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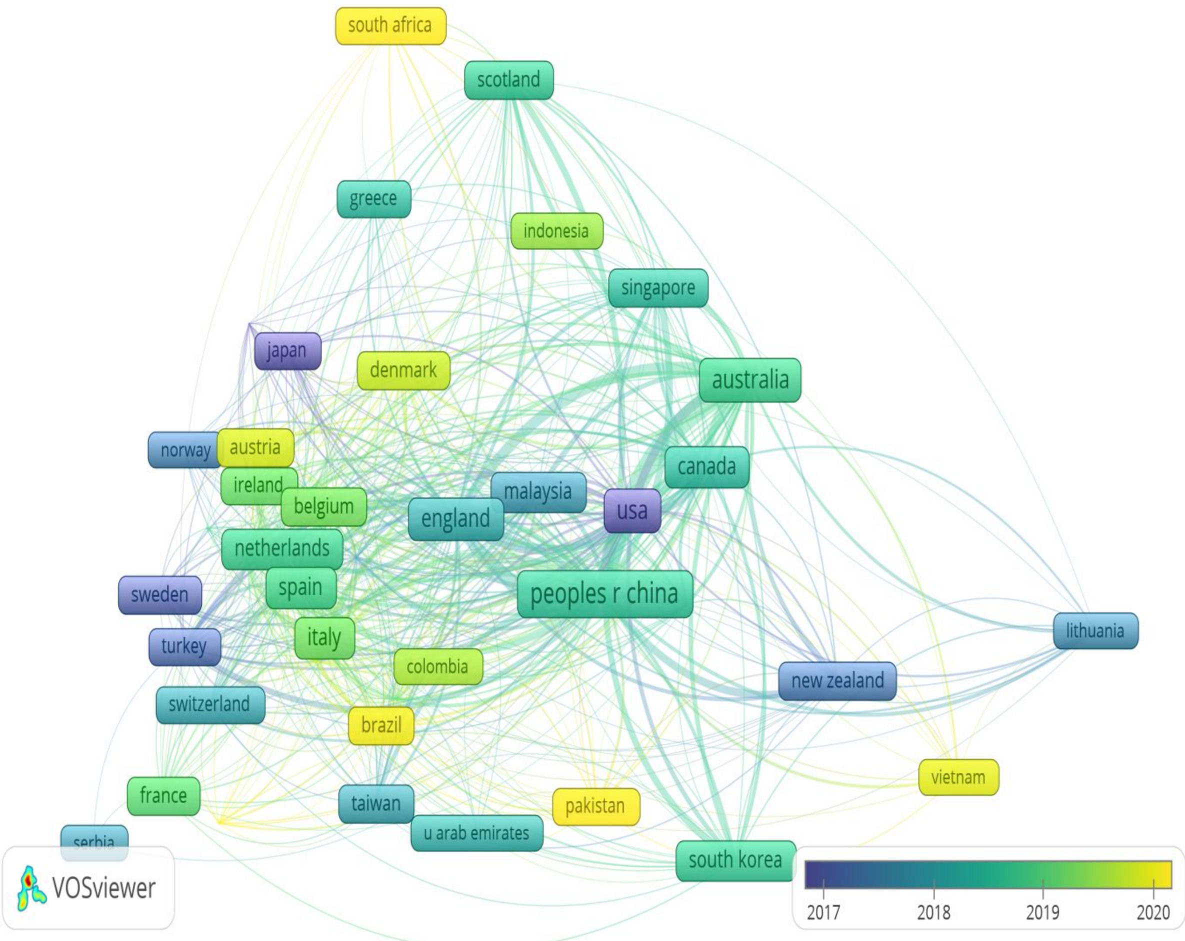

Figure 1: CE and OSC research by countries

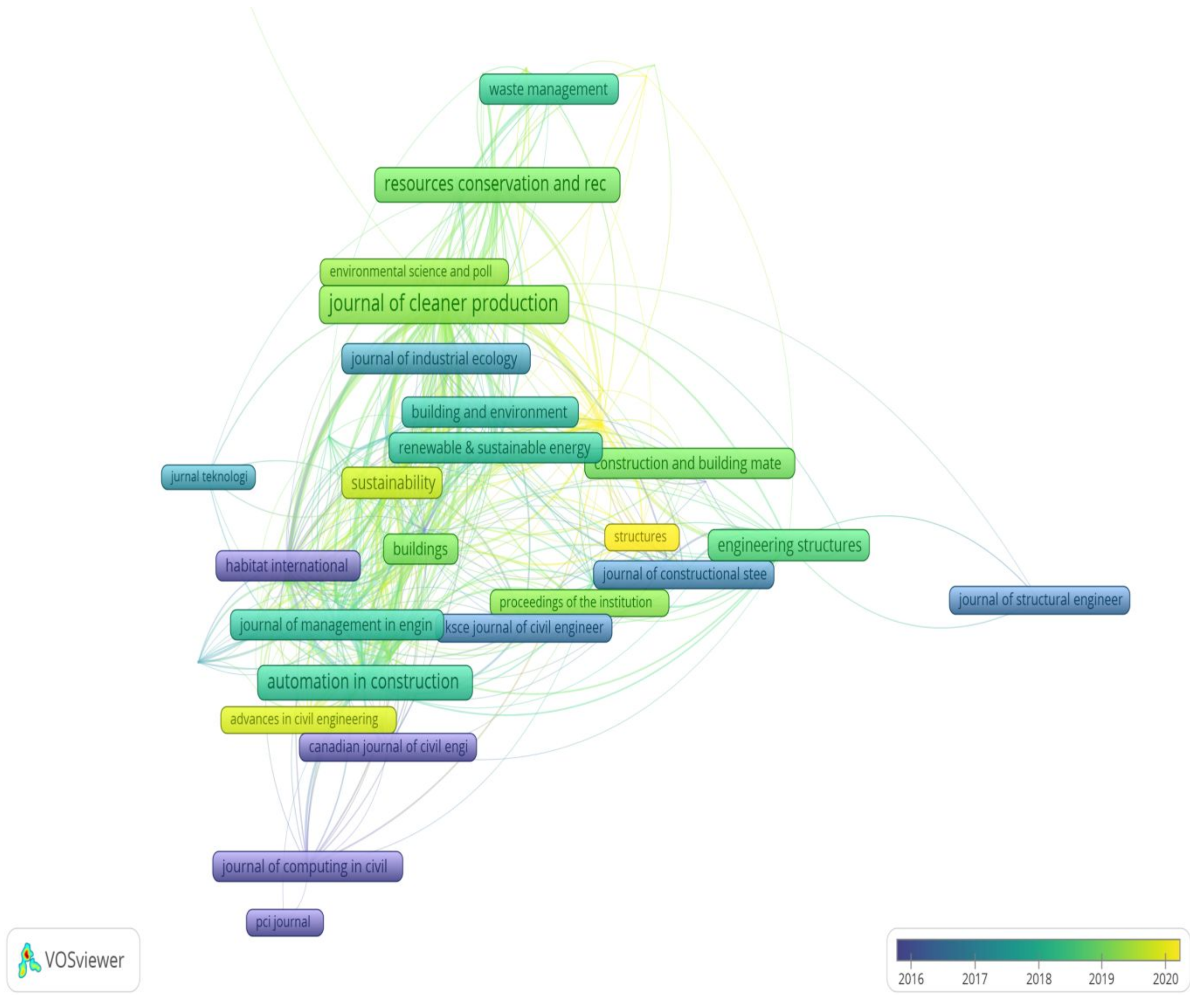

Figure 2: Outlets for publications in CE and OSC

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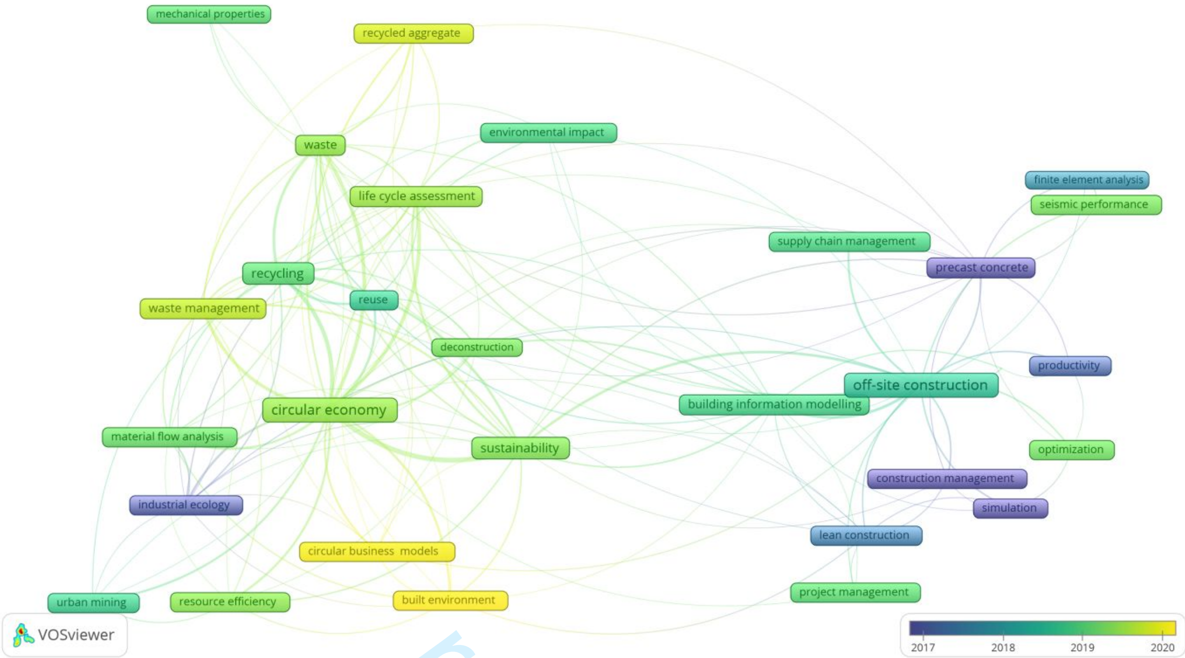

Figure 3: Keywords mapping by publication year

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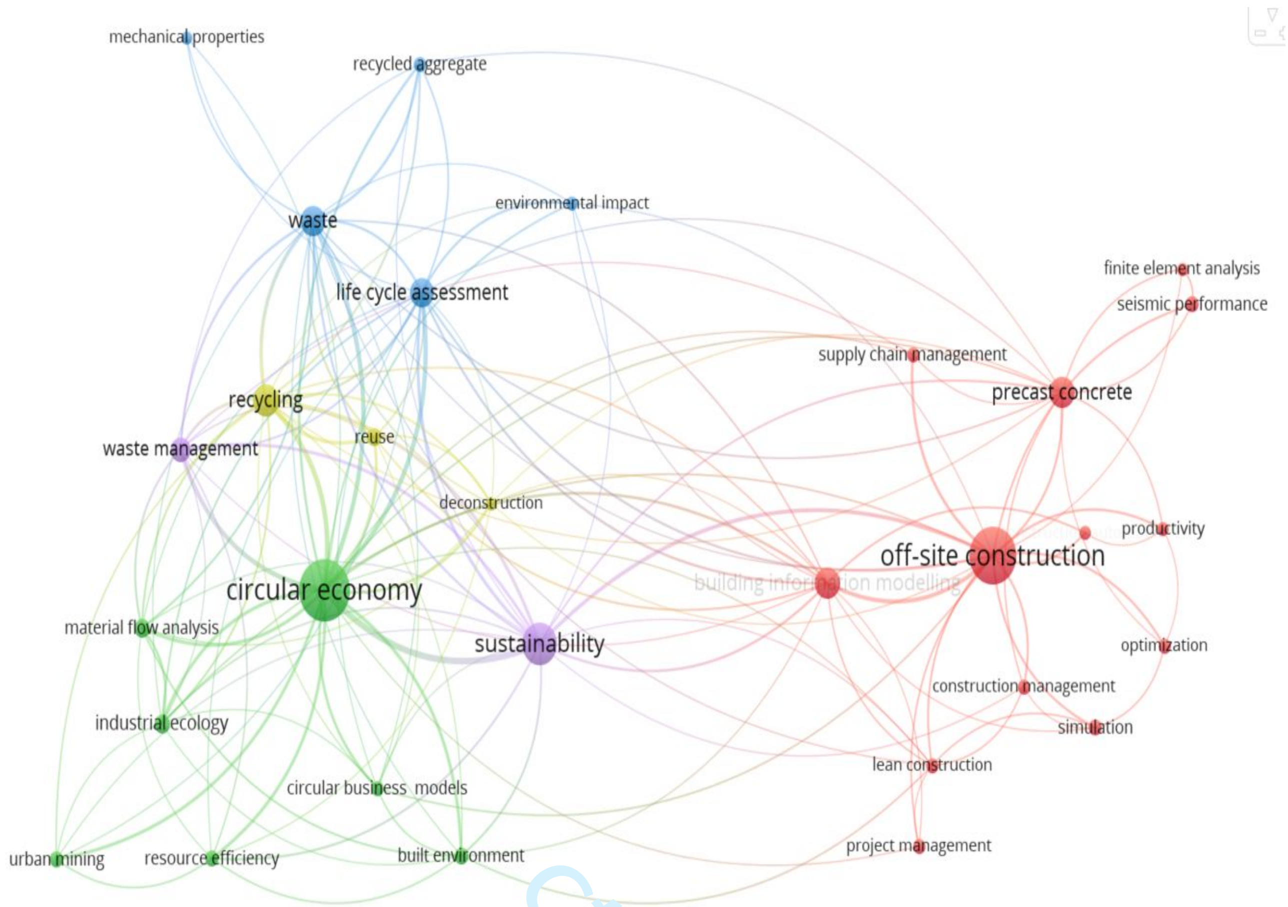

Figure 4: Keywords mapping by clusters

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Table I: Current research areas and future directions for integrating OSC and CE

Theme	Research areas	Concepts with current links for OSC and CE integration in literature	Future research directions	CE principles integrated into OSC
Product, process and technology	• Precast concrete • construction and project management, • supply chain management • lean construction productivity • Construction automation • Building information modelling (BIM) • Finite element analysis •	• Precast concrete, • BIM, • project management • Supply chain management, • lean construction	Promote BIM-enabled strategies/ tools for product, process, and management • BIM-based generative design for OSC • BIM-enabled CE performance analytics for OSC • BIM- enabled Material passport CE monitoring and assessment tool for OSC	Rethink Reduce Reuse
Circularity transition	• Material flow analysis, • industrial ecology, • circular business model, • urban mining • built environment • resource efficiency	• Circular business model • Built environment	Promote Circular business models for CE-enabled OSC delivery in the Built environment • new circular building construction system • Circular supply chain integration Value creation	Rethink
End of life	• Recycling, • Reuse, • Deconstruction	• Deconstruction	Promote Deconstruction-embedded design, manufacturing, and construction strategies • Design for Modularity • Design for manufacturing and assembly • Design for deconstruction	Rethink Recycle reuse
Sustainability waste management	• Sustainability • waste management	• Sustainability	Promote Sustainable design and Construction strategies • social sustainability of CE-embedded OSC products OSC	Rethink Recycle Reuse

			• recycled and reused materials on indoor environmental quality of OSC buildings • CE-based material passport analysis for OSC projects • OSC methods CE performance comparison	
Waste and environmental impact	• Life cycle assessment, • waste, • mechanical properties, • recycled aggregate • environmental impact •	• Life cycle assessment • Waste • Environmental impact	Life cycle-based waste minimisation strategies • Performance assessment of Recycled materials for OSC • Quantification of waste rates for CE-enabled OSC methods	Rethink Recycle Reuse

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