The Critique of Sustainability Discourse within the Off-Site Construction (OSC): A Systematic-Scientometric Review

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Abstract

Offsite Construction (OSC) continues to be perceived as a transformative vehicle and agent for empowering the predominantly labour-intensive construction industry (CI) to achieve heightened productivity. The contemporary socio-economic landscape demands that the Construction Industry (CI) assumes a broader responsibility beyond mere productivity; especially given its impact to global GHG emissions. In this respect, CI professionals are increasingly obliged to address sustainability concerns. Consequently, research endeavours have progressed to align with this overarching aim – ergo, to reconcile sustainability imperatives with economies of scale and intrinsic opportunities provided by OSC in this respect. Against this backdrop, this research examines the ongoing developments in OSC research. It uses the UK CI as the primary research lens, to critically evaluate the degree to which outcomes are aligned to core sustainability drivers and mandates. In doing so, it employs a systematic-scientometric review method to examine OSC interventions across three performance themes: "structural," "process," and "environmental." Research findings reveal the prevalence of diverse OSC terminologies and their axiological positioning, the corollary of which seem to exert significant influence on inference. Acknowledging this, a causal relationship model was developed to: establish causal interconnections among the identified themes; present a structured comparative analysis of the UK’s current position; and finally, to use these findings and observations against similar developed countries. This study posits that OSC’s purported emphasis on heightened environmental sensitivity is not without its flaws, notably the omission of ‘circularity’ within the performance themes. Moreover, it emphasises the need for greater integrated thinking. This is seen as a core inhibitor and barrier, which inter alia, not only stifles progress (cf. meeting sustainability objectives), but also fails to recognise the impact on performance – ergo, the importance of fostering integrated thinking across the OSC productivity-sustainability conundrum.

Keywords: Off-Site Construction; Modern Methods of Construction; Building Construction; Sustainable Construction; Performance; United Kingdom.
1.0 Introduction

The term Off-site construction (OSC) is often considered an innovative method of design, production and assembly (compared to ‘traditional’ construction approaches and methodologies). In this respect, several descriptions and typologies have been used to classify/codify OSC, some of which include: modern methods of construction; industrialised building systems; off-site construction/fabrication/production; pod technologies; modular construction; pre-cast panels/foundations, sub-assembly systems; volumetric/hybrid construction, factory assembled panels, kit of parts etc (Abanda et al., 2017; Ofari-Kurangu et al., 2022).

Notwithstanding these variants, the underlying philosophy of this approach is to move most (if not all) of the on-site work performed by professionals and workers into a controlled factory environment for design and manufacture; and when complete, to deliver the end product to site for final installation/assembly (Goulding and Rahimian, 2019; Hussein et al., 2021). Even though OSC has been widely researched in various forms and specification variations (in terms of material and building types), scholars appear to have unanimously agreed on the benefits and capabilities that OSC may offer over traditional construction, such as faster delivery, higher quality, improved occupational safety, and reduced waste (Hussein et al., 2021).

Stating OSC not only provides benefits and capacity enhancements to the construction industry (CI), but it also brings certain challenges. For instance, Hussain et al. (2021) identified the complex supply chain in OSC as a key challenge to the delivery of OSC projects. In addition, lack of accreditation for quality and durability, high initial costs, lack of competition, and the negative perception of the public due to the lack of design flexibility and unappealing aesthetic are some of the widely acknowledged challenges for OSC in the industry (Abanda et al., 2017; Ehwi et al., 2022).

Anecdotally, CI is considered a key contributor to the UK economy, generating £117 billion in revenue and two million jobs (HM Government, 2020). However, the UK CI has been repeatedly scrutinised over the last few decades for being wasteful, adversarial, fragmented, dominated by a few disciplines, reluctant to innovate, and poor at knowledge dissemination, revealing the ubiquitous immaturity as an industry (Egan, 1998). As a result of CI's long-standing opposition to adopting productive and sustainable practices, the government has been pushed to the point of mandating new policies such as MMC, Building Information Modelling (BIM), Net Zero Carbon 2050, etc. Further to this, the Egan Report (1998) took the lead in relaunching the initiative for innovation in the UK CI by highlighting "component production" as a priority.
in promoting cultural change for a more sustainable and productive UK CI. However, the underlying principle of OSC is not an entirely new concept for the UK CI. This construction method can be traced back to the old Roman occupation in Britain when the archaeological site of Lunt Fort near Coventry was built using timber components moved from elsewhere (Nazir et al., 2021).

Furthermore, during the post-WWII era, the UK deployed a prefab mission to meet the housing needs of a traumatised and displaced population, which proved to be a timely solution at the time but left long-term negative perceptions about the aesthetic, durability, and maintenance (Nazir et al., 2021). This was because the prefab dwellings of post-WWII era were poor in terms of durability and performance criteria, leading to a public perception of prefabricated buildings as being appropriate for temporary use and with no design flexibility. With such a decline in public appeal, UK CI was introduced to industrialised building concepts between 1950 and 1970, with the emphasis on a closed construction process in a factory setting, while leaving basic assembly activities on-site. Later, by the end of the 1970’s, UK CI further progressed towards volumetric construction, seeing the building construction as assembling a number of factory-produced aluminium panel boxes on-site and following up by adding services and utilities to those to form modular construction in the 1990’s. Lastly, in 2019, the UK government identified a MMC definition framework consisting of different OSC typologies with the same fundamental principle - see Fig. 1 (MHCLG, 2019).

This was complemented by Guidance Note in 2022 from the UK Government to provide policy context, platform considerations, contracts and best practice (OGL, 2022). In addition, other reports and initiatives of note include: KPMG (2016) *how offsite manufacturing can transform the industry*; Parliament (2018) *barriers to the wider uptake of off-site manufacture*; and HM Treasury (2021) *addressing productivity to build back better*. This echoes and aligns to previous offsite debate in the UK (Pan et al, 2008; Goodier and Gibb, 2007; Gibb, 1999); which inter alia, highlights that that OSC has had a distinct journey in the UK CI, through many different forms and variants, the corollary of which forms the basis and context of this research (given the need to further improve the UK CI).
While the OSC primarily accentuates CI's pursuit of productivity goals, the escalating global apprehension over climate change compels the CI to extend its accountability beyond mere productivity to encompass broader sustainability imperatives, including the imperative to curtail greenhouse gas (GHG) emissions. Du Plessis (2007) envisions sustainable construction as an all-encompassing endeavour that harmonises the natural and built environments, fostering constructions that not only serve economic interests but also affirm human dignity. Given that both "construction" and "sustainability" are terms laden with multifaceted meanings, their amalgamation only compounds the challenge of attaining a succinct definition (Du Plessis, 2007). Yet, the CI's position in this discourse on sustainability is accentuated by its accountability for a staggering 25% of global GHG emissions (Anderson et al., 2022).

Using this trajectory as a starting point, the political and economic significance of OSC in the UK has prompted an increasing number of studies to investigate OSC, particularly in relation to its ability to address core recurrent challenges such as productivity and sustainability. For example, Wuni, Shen and Osei-Kyei (2021) highlighted how UK OSC-related research could contributed to sustainability, including concomitant trends and themes. In addition, Nazir et al. (2021) conducted a UK bibliometric analysis to
highlight the advantages of modular construction techniques in housing versus traditional methods, particularly how modular could be used to address UK CI-wide challenges.

The prevailing discourse surrounding OSC has predominantly revolved around its economic viability, as evidenced by governmental (i.e., HM Treasury, 2021; Parliament, 2018) and industry reports (i.e., Farmer Report, 2016; Egan, 1998), emphasising productivity enhancement. However, our contention posits that such a focus overlooks the imperative to embed sustainability considerations within OSC, forming the rationale for this study. For instance, Li et al. (2022) argue that despite the focus on sustainability in OSC, persistent obstacles persist, particularly in yielding better environmental benefits while meeting economic expectations. Accordingly, the aforementioned studies and corresponding reports underscore the imperative of attaining a more profound and intricate comprehension of how OSC (and its derivatives) can be subjected to a purposeful critique against performance metrics. Initially, the introduction of OSC centred predominantly around productivity goals; however, the current global landscape, pursued by rapid GHG emissions and consequent climate change, demands broader accountability from the CI. As sustainability takes precedence, this study aims to offer insights into fundamental OSC initiatives, concepts, development, related taxonomies, and their ramifications in meeting these expanded sustainability concerns alongside productivity objectives. The study aims to bridge this existing gap by examining the state of the OSC concept as it pertains specifically to the UK CI, tracking trends over the past 22 years, thereby identifying deficiencies and potential avenues for growth to provide a roadmap for future research. While the global body of research on this topic is extensive, this study deliberately narrows its scope to analyse UK-centric studies. While some may perceive this decision as a limitation, authors construe this as a strategic manoeuvre aimed at facilitating a critical assessment of OSC’s trajectory.

2.0 Methodology

Fig. 2 presents the methodology used in this study consisted of two steps: the extraction of relevant bibliometric data from the selected databases and the review of selected bibliometric data using scientometric and systematic methods. Cheng and Song (2019) emphasised the review methodology comprising a combination of systematic and scientometric methods as a "systematic scientometric review,” which was adopted in this study.
2. Review methodology

2.1 Locating bibliometric data

Scopus and Web of Science were chosen as the research databases for locating relevant studies. This was because Hussein et al. (2021) recommended Scopus due to its extensive coverage, while also emphasising the importance of multiple databases to minimise biases. Therefore, the Web of Science was selected as the next source of scientific publications as it is connected to academic library tools. Subsequently, to facilitate the data location process, a comprehensive list of relevant and alternative keywords related to OSC...
Inclusion criteria

I. Published in indexed peer-reviewed journals or indexed conference proceedings

Publications in indexed and peer-reviewed journals, as well as conference proceedings, were seen to be of higher quality and more reliable.

II. Published between 2000 (January) - 2022 (November)

The year 2000 was chosen as the beginning point because the Egan Report, issued in 1998, officially prompted the UK CI for the first time to adopt the OSC underlying principles.

III. Published in English language

English is the common language for professionals and academics in the UK CI, and the authors of this SLR are proficient in it.

IV. Publications highlight at least one of the OSC terminologies

This SLR's focus is not confined to OSC as a terminology, but to any construction form that occupies the underlying principle behind it.

V. Publications report findings of the UK CI as fully or part of the study

This study is specific to the UK CI and how the OSC underlying principle has evolved and shaped the UK CI. Therefore, studies from other sectors like manufacturing were excluded, but studies discussing OSC in general and shedding light on its application to UK CI as part of a study have been included.

2.2 Selection of the most relevant bibliometric data

A list of inclusion criteria was used for selecting the most relevant research publications from the database-generated list of publications. The list of inclusion criteria is illustrated in Table 1.

Table 1. Inclusion criteria of research publications

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

The list of studies obtained from both databases underwent the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) evaluation (Moher et al., 2009), as depicted in Figure 3. Using the initial keyword search, a total of 427 studies were retrieved from both databases. After removing duplicates using EndNote reference management software, 170 duplicate studies were identified in the merged list of derived studies (Fig. 3).
Out of the 257 remaining studies, 87 were excluded based on abstract evaluation, with 70 deemed irrelevant and 17 identified as duplicates. The remaining 170 studies underwent full-text evaluation, resulting in the exclusion of 60 studies. This included 6 studies from the period of 2000-2005 due to unavailability of full-text and 54 studies that did not significantly contribute to the UK CI context. In the end, a total of 110 studies spanning from 2000 to 2022 were eligible for the systematic scientometric review.

### 2.3.1 Scientometric review

Hussein et al. (2021) emphasised the application of scientometric review as a mapping tool to visualise keyword connections and collaborations among researchers, institutions, and countries. To achieve this, the study employed the VOS viewer, a text-mining tool known for its capacity to visualise large networks and employ special text-mining features. The merged list of studies from EndNote was imported into the VOS viewer software to construct a network of co-occurring keywords. The overlay visualisation feature in the VOS viewer allowed for the examination of keyword co-occurrence patterns over a span of 22 years, revealing the evolution of OSC concepts.


2.3.2 Systematic review

The second stage of data analysis involved employing a systematic review methodology to examine the retrieved bibliometric data. While scientometric reviews have the advantage of facilitating network development within a study, their capacity to provide in-depth understanding of the study content is still considered limited (Liu et al., 2020). In this study, the 110 included studies were meticulously examined and investigated, resulting in the identification of three key performance themes: structural, process, and environmental, as depicted in Figure 02.

Despite its significant contributions, this study has limitations concerning the systematic literature review approach outlined by Denyer and Tranfield (2009), particularly regarding the sample criteria and analysis. Additionally, in the interest of brevity, certain scientometric analyses, such as the network of active institutions and researchers, were not included. Nevertheless, an analysis of the most cited studies provides insights into the active researchers and institutions in the UK context.

3.0 Research Findings of Scientometric Review

This section discusses the scientometric results provided by VOS Viewer, Scopus Citation Overview, and Web of Science Citation Report. The trajectory of publications over the last 22 years, the most cited journal/conference titles and studies, keyword-occurrence network, and citation burst analysis to indicate an OSC concept evolution are discussed.
3.1 Annual publication trend related to OSC in UK CI

Fig. 4 depicts the distribution of the included 110 studies across the study period, corroborating the premise that the subject of OSC is becoming increasingly prominent in the UK CI.

Figure 4. Annual research publications on off-site construction in the UK CI context

From 2016 onwards, there has been a notable increase in the consideration of Offsite Construction (OSC), averaging 9 studies annually, comprising 54.5% of the total. Prior to this period (2000-2016), the annual average was around three studies, indicating the early stages of OSC research. Noteworthy is the pre-downturn peak of studies in 2007, shaped by the 2008 financial crisis and construction boom in the industry during 2007 (Office for National Statistics [ONS], 2017). However, there was a peak of 14 studies in 2021, followed by 10 studies in 2019. While an overall upward trend is observed, certain years experienced a decline, attributed to external factors such as in 2020, due to the COVID-19 pandemic, and the lingering effects of the 2008-2009 financial crisis until 2017 (ONS, 2017), diverting attention from OSC research.

3.2 Analysis of most cited studies in the field of OSC in UK CI

This section analyses the co-citation of the top-cited publications on the OSC in the UK CI. In order to facilitate VOS viewer analysis, the selection criterion was set to a "minimum of 20 citations obtained by a document” to distinguish the most cited ten publications in OSC research. The following Table 2 summarises the top ten studies with the total number of citations and number of links (which shows how much they have been referred to by other studies in the same field).
Table 2. Top-cited publications on OSC in the UK CI

<table>
<thead>
<tr>
<th>Publication (Authors)</th>
<th>Published year</th>
<th>Total citations</th>
<th>Field-Weighted Citation Impact*</th>
<th>No of links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monahan J., Powell J.C.</td>
<td>2011</td>
<td>336</td>
<td>11.05</td>
<td>2</td>
</tr>
<tr>
<td>Pan W., Gibb A.F., Dainty A.R.J.</td>
<td>2007</td>
<td>227</td>
<td>4.52</td>
<td>4</td>
</tr>
<tr>
<td>Pan W., Gibb A.G.F., Dainty A.R.J.</td>
<td>2008</td>
<td>156</td>
<td>4.79</td>
<td>6</td>
</tr>
<tr>
<td>Alwan Z., Jones P., Holgate P.</td>
<td>2017</td>
<td>124</td>
<td>6.49</td>
<td>0</td>
</tr>
<tr>
<td>Arif M., Egbu C.</td>
<td>2010</td>
<td>124</td>
<td>3.55</td>
<td>2</td>
</tr>
<tr>
<td>Goulding J., Nadim W., Petridis P., Alshawi M.</td>
<td>2012</td>
<td>114</td>
<td>2.36</td>
<td>3</td>
</tr>
<tr>
<td>Nadim W., Goulding J.S.</td>
<td>2010</td>
<td>91</td>
<td>4.03</td>
<td>2</td>
</tr>
<tr>
<td>Taylor M.D.</td>
<td>2010</td>
<td>56</td>
<td>2.83</td>
<td>1</td>
</tr>
<tr>
<td>Doran D., Giannakis M.</td>
<td>2011</td>
<td>46</td>
<td>2.61</td>
<td>3</td>
</tr>
<tr>
<td>Sutrisna M., Goulding J.</td>
<td>2019</td>
<td>35</td>
<td>5.18</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3 highlights the top 10 most cited studies published between 2007 and 2019, shedding light on various aspects of OSC in the UK CI. To begin with, Mohan and Powell (2011) contributed a framework for assessing the lifecycle carbon emissions and energy of different OSC methods. The studies by Pan, Gibb and Dainty (2007; 2008) focus on the applicability of OSC in enhancing the productivity of UK housebuilders and strategies for overcoming implementation barriers. Lastly, Alwan, Jones and Holgate (2017) explored the potential of integrating BIM with MMC to drive the UK CI sector toward achieving sustainable goals.

3.3 Co-occurrence network of keywords

This section focuses on the interconnections and co-occurrence of keywords, forming a network that reveals the research subjects and their relationships over the analysed period. Generally, Co-occurrence networks of keywords serve as valuable tools for identifying trends, issues, and research gaps within a specific field of study (Hussein et al., 2021). Accordingly, Fig. 5, generated using VOS Viewer software, presents the resulting network based on bibliometric data. Among the 900 keywords found in the 110 included studies,
38 keywords met the initial criteria. The resulting clusters of keywords are depicted in Fig. 5 using network visualisation techniques.

*Note: The keywords "United Kingdom", "offsite construction", "modular construction", "prefabricated construction" and "modern methods of construction" used in literature searches were removed from the above diagram for better clarity.

Each node in a keyword occurrence network is assigned to a particular keyword. Whereas the node size indicates how frequently it has been used (number of studies) within the research stream. Furthermore, a line connecting two nodes indicates their connectedness, whereas line thickness reflects frequency. Notably, the following deductions are derived from the co-occurrence of keywords through the "network visualisation" mode. Considering UK CI (Fig. 6(a)), the keyword "off-site construction" (30 occurrences) is mentioned more than "modular construction" (28 occurrences), "prefabricated construction" (20 occurrences), and "modern methods of construction" (19 occurrences). On the other hand, regarding how well researched those OSC typologies are in the UK CI context, the total link strength of each OSC form was looked at, and it revealed that "offsite construction" has the highest link strength, followed by "modular construction", "modern methods of construction", and "prefabricated construction". As a result, Fig. 6(b), (c), (d), and (e) show the most frequently used keywords for "offsite construction," "modular construction," "prefabricated construction," and "modern methods of construction," respectively.
Figure 6. The keywords networks of (a) UK CI; (b) offsite construction; (c) modular construction; (d) prefabricated construction; (e) modern methods of construction; (f) housing.
It is worth noting that OSC research has been conducted throughout the construction product supply chain, indicating the links (Figure 6(b)) with keywords such as "architectural design," "structural design," "design methodology/approach," "manufacture," and "standardisation," as well as other typologies. When considering "modular construction," however, the above research scope appears to have been expanded into the process aspects of OSC derived from its high link strengths with the keywords "sustainability," "energy efficiency," and "carbon dioxide" (Fig. 6(c)). In addition, "prefabricated construction" seems to be more concentrated around concrete-based production with its links to "pre-cast concrete," "concrete construction," and "wall (structural partitions)." As noted in the preceding section (Fig. 1), "modern methods of construction" has recently been introduced as an umbrella term covering on-site and manufacturing aspects, as well as site-based process aspects, which collaborates with the keyword network (Fig. 6(e)) towards the inclusion of "building information modelling," "sustainability," "cost-effectiveness," and "energy efficiency."

The detailed analysis of keyword occurrences highlights a distinct shift in the focus of OSC within the UK Construction Industry. Previously centred on enhancing productivity in factory settings, there is now a noticeable trend towards integrating considerations of energy and technology to address sustainability issues (Wuni et al., 2021). Specifically, keywords associated with sustainability and sustainable development, such as energy efficiency, carbon dioxide, cost effectiveness, building information modelling, structural design, concrete, and timber (Figure 5), emphasise a broader commitment to sustainability performance in OSC, particularly focusing on environmental and economic aspects, rather than placing emphasis on social characteristics, as outlined in Krug and Miles (2013).

Considering the types of construction projects, the relevance of housing projects in the OSC context takes precedence (Fig. 6(f)). Additionally, regarding the materials used in OSC processes in the UK CI, the keyword "timber" has been mostly highlighted. On the other hand, pre-cast concrete and steel have followed up as the next most used materials in the UK CI for OSC, respectively. In fact, Rajanayagam et al. (2021) and Iacovidou et al. (2021) particularly corroborate this finding, stating that the popularity of timber applications for modular houses and related OSC structures has risen owing to UK CI's pledge to reduce carbon footprints.
3.3.1 The evolution of OSC concept in the UK CI

As identified in Section 1, the seminal literature has introduced various terminologies related to OSC, resulting in a conceptual evolution over time. In order to analyse this evolution scientifically, two methods were employed. Firstly, a citation burst analysis (refer to Figure 7 (a) using CiteSpace software identified keywords that experienced significant increases in citations over a span of 22 years. Secondly, the VOS viewer's overlay mode (refer to Figure 7 (b)) was used to visualise the network of keyword occurrences and depict the influence of existing UK CI on the development of the OSC concept.

Additionally, the red line in Figure 7(a) represents the duration of citation influxes received by each keyword. The analysis reveals that the term "prefabricated construction" was prominent in early research conducted between 2000 and 2010, likely due to the UK CI's involvement in post-World War II prefab initiatives. Subsequently, the terms "offsite construction" and "modular construction" gained popularity, with the latter term emerging more prominently after 2014. Notably, since 2017, the concept of MMC has gained traction, credits to the UK government's efforts to redefine it as a common terminology encompassing various terms sharing the same fundamental premise.

Regarding the UK CI OSC terminologies, it was observed that initially, the focus of OSC concepts, specifically prefabricated construction, was centred on concrete-based construction methods and the economic viability of OSC implementation. As the field evolved, the concepts of MMC and OSC gained prominence, expanding the narrative to encompass design and structural considerations of OSC-based buildings and components. Moreover, in the realm of OSC, sustainability and the pursuit of sustainable development goals have emerged as critical imperatives. Researchers have proactively delved into exploring alternative materials like timber and steel, seeking to supplant carbon-intensive precast concrete. This shift underscores a growing focus on mitigating the environmental impact of OSC. Notably, the latter phase of OSC within the UK CI from 2017 onwards has witnessed a noteworthy innovation. A strategic adoption of digital technologies has been embraced to bolster productivity and address complexities within the supply chain.

Furthermore, a deliberate emphasis has been placed on achieving sustainability through meticulous tracing and accounting of whole-life embodied carbon. This evidences a purposeful endeavour to revolutionise traditional construction processes by embracing industrialisation and harnessing digitalisation to yield
improved productivity and sustainability outcomes. Overall, the research conducted in the context of OSC within the UK CI demonstrates a concerted and determined effort to transform conventional practices by embracing an industrialised approach. Concordantly, the seamless integration of digital technologies acts as a catalyst for enhancing productivity and advancing the pursuit of sustainability objectives.

Figure 7. (a) the citation burst analysis of keywords through Cite Space 6.1.R1

Figure 7. (b) Overlay co-occurrence of keywords through VOS Viewer
It is crucial to acknowledge the limitations inherent in scientometric methods, as highlighted by previous research (Hussein et al., 2021; Ehwi et al., 2022). To address these limitations, a rigorous systematic review was undertaken. This systematic review aimed to enhance the reliability and credibility of the findings. Notably, the clustering function of VOS viewer played a pivotal role in establishing a more coherent classification for the systematic review. The analysis of the studies revealed three dominant performance themes in the UK CI pertaining to OSC: structural performance, process performance, and environmental performance. Figure 8 presents the distribution of included studies across these performance themes over the analysed period.

During the formative years (2000-2010), the predominant focus was centred on delving into the fundamental principles of OSC. The objective was to enhance the performance of building elements and materials, while also refining overall process performance encompassing procurement practices and digitalisation. However, from 2010, the research landscape gradually transformed, shifting towards an exploration of how technological advancements and organisational management aspects, including BIM, virtual reality, and lean principles.

This paradigm shift reflects a burgeoning interest in harnessing technology and efficient management practices to optimise OSC processes. Furthermore, over the past eight years of the analysed period, a
discernible integration of environmental performance has emerged as a mainstream theme, underscoring the industry's commitment to addressing ecological concerns and striving for sustainable OSC practices. The identified performance themes are discussed in the next sections in terms of how the OSC, its related forms, and underlying principles have contributed to enhancing each performance theme through the analysis of the most relevant studies out of the 110 included studies.

4.1 Structural performance theme

The structural performance of OSC-based building structures oversees a structure's stability under natural and man-made stresses by transmitting such loads to the building foundation via structural components, non-structural components, and inter-component connections. Therefore, this section illustrates how the OSC, and its underlying principles have evolved within UK CI to improve structural performance by calibrating building components, connections among such components, and adopting advanced construction materials.

4.1.1 Structural performance through building components and connections

The systematic review findings indicate that early OSC research primarily focused on the manufacturing or pre-casting of specific structural components outside the physical construction site, known as component manufacturing. Initially, Witham (2005) discussed the rapid development of uniform structures, by identifying which structural components could be prefabricated or mass manufactured. Then, in extending the component manufacturing scope, Feenan (2008) explored improving the structural stability of prefabricated components through the cross-wall construction method, enabling enhanced lateral stability by connecting prefabricated walls. However, the use of the volumetric pre-assembly method in "The Shard" marks a significant milestone in advancing structural performance. This approach provided much usable space compared to traditional non-volumetric pre-assembly methods (Parker, 2013). The success and innovation demonstrated by the Shard's construction propelled the UK CI towards embracing a wide range of new assembly methods. This shift towards new assembly methods signifies a progressive mindset within the CI, as it pursued to maximize efficiency and overcome spatial limitations (Banks et al., 2018).

However, cognisant of this, it is equally imperative to acknowledge the challenges of modular construction, particularly related to its complex supply chain. For instance, integrating exterior façade and internal finishing with the structural module often results in compatibility issues, leading to unexpected delays and...
waste (Nazir et al., 2021). To address these complexities, CI professionals sought to embed primary structural modules with all necessary building internal fitouts and services at the factory production stage, simplifying the process by reducing reliance on multiple suppliers and manufacturers. In fact, Hayes (2019) referred to this as an industrialised building system (IBS) or volumetric/modular building system (V/MBS), representing a further step towards industrialisation by shifting tasks to a factory environment.

Evidently, the evolution of OSC research in the UK CI has progressed along the industrialisation pathway, from component manufacturing to the production of fully equipped 3D building units. This simplification of the supply chain aims to consolidate construction activities in a single factory environment, leading to improved productivity (through standardisation and specialisation) and sustainability (through efficient resource management and waste reduction) in OSC projects, as acknowledged by Nawi et al. (2019). Figure 9 summarises the evolution of structural performance in the UK CI, with a specific focus on building component manufacturing.

**Figure 9.** Progression of OSC building manufacturing

Unlike traditional buildings, the structural integrity of OSC buildings, as depicted in Fig. 9, relies heavily on the connections used to transfer lateral loads to structural elements. In fact, Rajanayagam et al. (2021) emphasised the importance of structural integrity in modular-based construction, highlighting the presence of multiple substructures (modules) with their own frame schemes. Ultimately, this complexity of connecting modules to the main structural frame has prompted extensive research on the strength of beam and column connections within modules to withstand shear, bending, and lateral loads. Nonetheless, Rajanayagam et al. (2021) recognised that connections not only contribute to structural integrity but also
have the potential to facilitate the reuse and recycling of prefabricated/modular components, leading to waste reduction. Table 3 discusses the three main connection types found in the included studies.

Table 3: The OSC connection mechanisms and their sustainability aspects

<table>
<thead>
<tr>
<th>Connection Mechanism</th>
<th>Description</th>
<th>Included Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Welding</strong></td>
<td>Two modules or frames are connected at a point with melted materials. In the included studies, it can be noted that the welding mechanism has been prominent with connections that have steel components, irrespective of whether they are steel structural frames or modules. The lack of sustainability has been noted as the welded elements cannot be dismounted and reused, resulting in waste.</td>
<td>(Rajanayagam et al., 2021); (Hayes, 2019)</td>
</tr>
<tr>
<td><strong>Bolted</strong></td>
<td>The bolts are used to fasten the two elements via the metal base. The possibility of reusing the elements and connections in these connections resulted in minimising waste and enabling the dismounting process as a means of achieving sustainability.</td>
<td>(Koronaki et al., 2021); (Duncheva and Bradley, 2019)</td>
</tr>
<tr>
<td><strong>Composite/ Hybrid (Concrete-steel)</strong></td>
<td>The composite connecting mechanism works on the same principle as bolted connections, with the main difference being that connections are made among components with different materials. This mechanism has been widely used, especially in building high-rise modular buildings where the modules and steel frames are mounted to a concrete core. The inability to demount limits reuse of composite connections, resulting in waste under this method.</td>
<td>(Rajanayagam et al., 2021); (Parker, 2013)</td>
</tr>
</tbody>
</table>

Therefore, it is evident that the OSC research in the UK CI has shown a clear focus on industrialising the building construction process to standardise supply chain activities and enhance productivity within the structural performance theme. Simultaneously, the studies within this theme have also emphasised sustainability by addressing waste reduction and quality control in production processes and building connections (Parker, 2013; Hayes, 2019).

4.1.2 Structural performance through improving material specifications

In respect of scientometric review findings, materials such as timber, steel, and concrete are the dominant materials in the OSC market (refer to Figure 5), whereas a systematic review highlights the preference for precast concrete, particularly with a high proportion of Portland cement, in early UK CI research (2000-2010) for component manufacturing.

From a concrete viewpoint, Milner (2006) emphasises the use of fastcast concrete for precast floors and shear walls, citing its durability. Along with this, Feenan (2008) addresses the energy-intensive production process of Portland cement and suggests exploring alternative materials. Owing to address limitations of precast concrete, such as thermal cracking and workability issues, Parker (2013) introduces ground-granulated blast furnace slag (GGBS), as a replacement for 70% of Portland cement, improving the quality of precast concrete and reducing carbon emissions. Similarly, Canning and Luke (2010) explore the use of
fibre-reinforced polymer (FRP) as an admixture in concrete to reduce the weight of prefabricated components. Eventually, the direction of enhancing the structural performance of precast concrete has been continued by Marcinkiewicz and Wells (2014) using fibre reinforcements and Lee (2021) using Silica Fume (SF) as an additive to improve compactness.

**From a steel viewpoint**, the incorporation of steel into OSC has been widely researched. Firstly, Pan et al. (2011) highlight the use of cold-formed steel (CFS) for manufacturing lightweight and high-strength steel frame components. On the contrary, Feenan (2008) points out challenges associated with CFS, such as buckling and web crippling, necessitating optimisation for preserving the structural integrity of MBS. Unlike precast concrete, where optimisation focuses on material composition, the performance optimisation of steel components in the included studies involves varying the cross-sectional design (Iacovidou et al., 2021; Hayes, 2019). Apart from this, Hayes (2019) investigates the use of hot-rolled steel in volumetric construction by developing a structural design. Nonetheless, in terms of sustainability, Nawi et al. (2018) advocate for the use of steel over concrete due to its near 100% recycling rate, maximising material efficiency, reducing waste, and promoting sustainability.

**From a timber viewpoint**, scientometric review findings indicate that timber is a prominent material in UK OSC, alongside steel and concrete. While timber has been traditionally associated with frame manufacturing, Silbert (2006) emphasises the need to address associated risks of fire hazards in timber framed OSC. However, it is worth noting that the recent OSC research has expanded timber integration from component manufacturing to the production of non-volumetric and volumetric preassembled elements. In respect of that, Rodrigues et al. (2016) highlight the use of timber optimisation techniques, specifically "cross lamination of timber," to manufacture solid structural panels with high load-bearing strength. On the other hand, Zaccaro et al. (2021) emphasise the need to improve the thermal performance of outer timber closed panels through a Fabric-First Approach (FFA), enhancing airtightness and minimising thermal transmission. However, the requirement for skilled on-site labour for timber element assembly and connections has been recognised as a barrier to comprehensive industrialisation (Gee and Brown, 2022).
Overall, it is notable that OSC-based research in the UK CI has primarily concentrated on enhancing material composition and design profiles to enhance the structural integrity of OSC structures while considering the environmental impact of the materials used.

4.2 Process performance theme

Scientometric findings highlight the importance of procurement methods and technological intervention in improving the speed, accuracy, and sustainability of OSC projects in the UK CI. Accordingly, this section explores the evolution of supply chain process aspects in UK CI OSC projects through enhanced procurement strategies and the adoption of technologies to improve project delivery.

4.2.1 Process performance through advancing the procurement strategies

The systematic review indicated that early OSC research in the UK CI aimed to avoid further complicating the construction supply chain by involving third-party manufacturing of specific building elements (Pan et al., 2007; Pan et al., 2009). As part of this, Stephenson and Kirkham (2005) emphasised the need for a standardised protocol for the supply and assembly of modular components, allowing clients to identify OSC components and integrate them using innovative procurement methods like Private Finance Initiative (PFI) and Public Private Partnership (PPP) based on the partnering concept.

Meanwhile, Pan et al. (2007) explored the perceptions of UK housebuilders regarding OSC and identified complexities arising from the integration of traditional and industrialised construction, lack of definition, limited trust, and communication among stakeholders as major barriers. In looking for solutions to simplify the complex OSC supply chain, Pan et al. (2009) emphasised the need for a leading role to drive innovation and manage the OSC supply chain, proposing to establish an in-house management mechanism within manufacturers/builders to streamline design, procurement, and construction/assembly processes.

Nevertheless, early suggestions regarding process enhancement through procurement strategies have been extensively explored in subsequent studies. For instance, Charlson and Dimka (2021) introduced the "Design for Manufacturing and Assembly" (DfMA) approach in the context of modular construction, aiming to optimise OSC processes. Similarly, Banks et al. (2018) highlighted the potential of integrating on-site operations and component-based assembly through DfMA to revolutionise traditional OSC construction. As a result, DfMA-enabled OSC initiatives attempt to identify, evaluate, and eliminate waste and inefficiencies throughout the OSC-based product design, manufacturing, and assembly processes.
resulting in improved productivity while stepping towards the sustainability goals (Charlson and Dimka, 2021).

Simultaneously, UK scholars advocate for integrating lean manufacturing strategies to optimise production processes and on-site assembly, aiming to eradicate non-value-added activities. For instance, Gomez et al. (2021) underscore the potential of Just-in-Time (JIT) to ensure precise material delivery for production, thus reducing inventory and waste. However, Goh and Goh (2019) suggest that integrated lean manufacturing strategies would be more viable than implementing an absolute lean manufacturing strategy due to industry uncertainties.

Overall, research in OSC within the UK has sought to address inherent complexities in the OSC supply chain. The objective found to be enhanced productivity and reduced waste by improving information management and minimising non-value-added activities. Subsequent research in this theme aimed to adopt an “in-house” management approach, directing the entire supply chain toward innovation, a concept later known as DfMA. Additionally, the research emphasises the importance of considering environmental sustainability in both design and processes when determining the most suitable procurement pathway.

4.2.2 Process performance through adopting digital technologies

The UK government's commitment to digitise UK CI through BIM has had a significant impact on OSC, where the emergence of BIM technology is pervasive in scientometric review findings. Considering the systematic review findings, Goulding et al. (2012) were among the pioneers in incorporating technology into the OSC process by introducing virtual reality (VR). Their work involved developing a VR-powered prototype environment for training OSC personnel, aiming to minimise waste and enhance productivity by proactively addressing faults.

On the other hand, Alwan et al. (2017) examined the potential of BIM beyond its traditional role of oversight. In fact, Alwan et al. (2017) revealed that BIM, when combined with MMC, enables iterative design modifications during the construction stage, ensuring precise and sustainable material usage, thus minimising wastage. Further, Sutrisna and Goulding (2019) explored the information management aspect of BIM integration in OSC projects, revealing the reluctance of UK CI stakeholders to embrace OSC, primarily due to the knowledge gap and limited access to site-specific information faced by manufacturing professionals. To overcome these challenges, Sutrisna and Goulding (2019) advocated for BIM as a solution.
to incorporate real-time site conditions into the design process and create an interoperable environment for seamless collaboration among supply chain actors. On the other hand, Iacovidou et al. (2021) demonstrated the significance of digital intervention in OSC by extending its application to maintenance and disassembly processes. Their findings highlighted the role of digital intervention, particularly BIM integrated with radio frequency identification (RFID), in promoting component reuse and achieving sustainable performance. This integration facilitated the creation of an on-site information-sharing environment accessible to various supply chain actors involved in the asset's life cycle, including clients, design, construction, and maintenance service providers.

While the focus of the included studies revolves around enhancing technology-enabled process performance through information management aspects, the integration of digital technologies like robotics, 3D printers, autonomous vehicles, and drones into the physical processes of OSC has been a subject of recent studies, a prospect formerly underlined by Goodier and Gibb (2007). Notably, Tobi et al. (2018) assert the economic viability of 3D-printed UK houses, against traditional methods, while Taylor (2022) advocates the integration of robotic arms in the factory assembly of precast elements as a remedy for the escalating shortage of skilled labour. Collectively, the reviewed literature concentrates on the infusion of digital technologies into physical process enhancements within factory environments.

Overall, the studies reviewed emphasise the critical role of digital intervention in enhancing process performance through information and physical manufacturing aspects as illustrated in the Table 4. Earlier studies focused on overcoming interoperability challenges among stakeholders, leading to increased productivity through effective information management and waste reduction. Notably, the adoption of BIM for design and construction has been prevalent in OSC research. Subsequent studies expanded the scope of BIM application to encompass operation and maintenance (O&M) stages, integrating it with other technologies such as RFID, thereby offering comprehensive asset monitoring solutions throughout its entire life cycle.

**Table 4:** Summary of the evolution of OSC’s performance-oriented studies in the UK CI.
<table>
<thead>
<tr>
<th>Advancing Procurement Strategies</th>
<th>Third-party manufacturing complexity avoidance</th>
<th>Efforts to simplify the OSC supply chain by avoiding complications associated with third-party contributions for specific building elements.</th>
<th>Pan et al. (2007), Pan et al. (2009).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lean manufacturing integration</td>
<td>Strategic shift aiming to optimise production and on-site assembly, eliminating non-value-added activities, and enhancing overall efficiency.</td>
<td>Gomez et al. (2021), Goh and Goh (2019)</td>
<td></td>
</tr>
<tr>
<td>Design for Manufacturing and Assembly (DfMA)</td>
<td>Innovative OSC product design approach expanding traditional design to integrate on-site operations and component-based assembly.</td>
<td>Charlson and Dimka (2021), Banks et al. (2018)</td>
<td></td>
</tr>
<tr>
<td>Adopting Digital Technologies</td>
<td>BIM-enabled iterative design modifications</td>
<td>Recognition of BIM's ability to facilitate iterative design modifications, enhancing project flexibility, precision, and promoting sustainable material usage with minimised waste.</td>
<td>Goulding et al. (2012), Alwan et al. (2017)</td>
</tr>
<tr>
<td></td>
<td>Information management through BIM integration</td>
<td>Utilisation of BIM integration to overcome knowledge gaps and foster real-time collaboration among stakeholders, leading to a streamlined and efficient supply chain.</td>
<td>Sutrisna and Goulding (2019)</td>
</tr>
<tr>
<td></td>
<td>Digital intervention in maintenance and disassembly</td>
<td>Expansion of digital technologies beyond construction stages to optimise maintenance and disassembly processes, contributing to sustainable performance through enhanced component reuse.</td>
<td>Iacovidou et al. (2021)</td>
</tr>
<tr>
<td></td>
<td>Physical process enhancements with digital technologies</td>
<td>Application of digital technologies to enhance manufacturing processes in factory environments, addressing challenges like skilled labour shortages and promoting economic viability.</td>
<td>Tobi et al. (2018), Taylor (2022)</td>
</tr>
</tbody>
</table>

4.3 Environmental performance theme

Globally, the construction sector and its allied industries are facing increasing pressure to prioritise environmental sustainability and take responsibility for their impact. Leading reports, protocols, and mandates have recognised the need for change in these sectors. Therefore, this section explores how the concepts and practices related to OSC have evolved to align with the sustainable development goal (SDG 13: climate action) and address environmental concerns without compromising productivity.

Monahan and Powell (2011) played a pioneering role by conducting a comprehensive embodied carbon assessment of a timber panel-based modular house, emphasising the importance of considering OSC's environmental impact. To further mitigate the carbon footprint of OSC methods, Mohan and Powell also suggested exploring alternative materials like GGBS or fly ash as substitutes for Portland cement.
Similarly, Parker (2013) highlighted the integration of GGBS in precast concrete for the construction of the Shard, resulting in the reduction of 700 tonnes of carbon emissions from the base slab alone. On the other hand, as a further extension of environmental performance, Amiri, Caddock, and Whitehead (2013) introduced the concept of "carbon dioxide payback," which involves offsetting carbon dioxide emissions in the supply chain through carbon sink activities. However, subsequent research has criticised carbon payback as a temporary solution, highlighting that the CI cannot solely rely on tree planting or social initiatives (Anderson et al., 2022; Ismail et al., 2021).

In respect of operational energy aspects, Rodrigues et al. (2016) emphasised the significance of the design approaches such as “Passivhaus” in reducing energy usage and embodied carbon throughout the life cycle of a modular asset, which was further supported by Ismail et al. (2021). In a different direction, Jankovic (2019) utilised OSC principles for energy retrofitting by creating a thermal envelope around existing buildings. By this means, Jankovic (2019) revealed the potential of OSC not only for environmental performance but also for improving the sustainability of traditional buildings. Meanwhile, Mignacca and Locatelli (2021) established the role of modularisation in achieving a circular economy by reusing and recycling building components, calling for government recognition of this aspect to promote sustainability goals. In general, modularisation enables standardised designs and components that can be reused and recycled in future buildings, reducing the demand for raw materials and component production and advancing sustainability efforts. A summary of included studies under the theme of environmental performance is illustrated in the below Table 5.

Table 5: Summary of selected environmental performance-related studies and their major findings

<table>
<thead>
<tr>
<th>No</th>
<th>Study</th>
<th>OSC Type</th>
<th>Type of Building</th>
<th>Assessment Type</th>
<th>Building performance studied</th>
<th>Methodology</th>
<th>Major findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monahan and Powell (2011)</td>
<td>Panelised Modular Timber Frame</td>
<td>Residential</td>
<td>Partial Lifecycle Assessment (Cradle to site)</td>
<td>Embodied carbon assessment</td>
<td>ISO-14040 LCA framework was applied to compare embodied carbon in a modular timber frame house with traditional alternatives.</td>
<td>34% reduction compared to traditional construction. Concrete, despite being a minor material, contributes 36% to embodied carbon.</td>
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<tr>
<td>4</td>
<td>Rodrigues et al. (2016)</td>
<td>Prefabricated Timber Modular Residential</td>
<td>Overheating Occurrence</td>
<td>Thermal comfort of indoors</td>
<td>Simulation methodology using EDSL Tas, dynamic simulations to evaluate performance in current climate conditions.</td>
<td>Reduction in overheating observed with additional layers of Rigidur H and PCM boards. PCM boards effective in lowering overheating levels.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Jankovic (2019)</td>
<td>Panelised Residential</td>
<td>Deep Energy Retrofit</td>
<td>Thermal comfort of indoors</td>
<td>Using a ‘TCosy’ approach in which the existing building is surrounded by a new thermal envelope.</td>
<td>Ability to use OSC methods in developing energy envelopes for the existing building stock. 42% improvement in building energy performance post-retrofit. Discrepancy of over 60% between theoretical and measured UA values.</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Ismail et al. (2021)</td>
<td>Prefabricated modular Non-residential (University Building)</td>
<td>Energy audit</td>
<td>Assessment of climate change impact on energy consumption</td>
<td>Measuring the energy demand and carbon dioxide emission of the building based on heating degree-days theory, analytical degree-days approach, climate change scenarios (A1B and A1F1), carbon intensity projections.</td>
<td>The study verifies energy efficiency in prefabricated buildings. Projections suggested a potential 12% and 34% reduction in heating-related energy consumption by 2030 and 2080, respectively, highlighting prefabricated buildings' promising efficiency over traditional counterparts.</td>
<td></td>
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</table>

Overall, it is evident that the environmental performance theme in UK OSC is still emerging, with a focus on assessing embodied carbon emissions to compare sustainability between OSC and traditional construction methods. Recent research on this theme, however, has sought to extend the scope of carbon assessment beyond individual projects and encompass the entire supply chain, incorporating the principles of the circular economy.

### 5.0 Discussion of Findings

Arguably, OSC-related research in the UK stands at a pivotal moment, characterised by the evolution and maturation of several research themes over the past two decades. In this regard, researchers should no longer see OSC solely as an adjunct to manufacturing or component assembly, as it once was. Instead, research endeavours should encompass a broad range of interconnected themes and strategies that systematically leverage OSC, thereby facilitating the pursuit of net-zero initiatives. This section critically discusses the findings of this study in comparison to OSC in other developed economies, serving as a benchmark for improvement and identifying potential gaps. These considerations have been instrumental in formulating a
Causal Relationship Model (refer to Figure 10), employing three primary conduits: "Structural," "Process," and "Environmental." These conduits can be viewed as OSC ‘enablers’, allowing for the visualisation and contextualisation of current and future research trajectories.

5.1 Structural Performance Conduit

Building structural performance through OSC has reached a state of maturity, garnering heightened attention and becoming a focal point of study over the last two decades. The building production process is becoming more industrialised, with early component manufacture (Witham, 2005; Feenan, 2008) being overtaken by composite building systems (Parker, 2013, Hayes, 2019). The OSC’s timely maturation has somewhat mitigated the industry’s growing dependence on the workforce and added impacts from socioeconomic situations such as ‘Brexit’, thus largely preserving productivity goals. Adherence to sustainability in structural aspects of OSC has lately captured the attention, where component and building module reuse and recycling have prompted a circular economic model to be formed. Research exploring connection mechanisms has played a major role determining the OSC’s evolution in this direction (Rajanayagam et al., 2021; Hayes, 2019), demonstrating the significance of environmental sensitivity as a part of the UK CI’s strategic directives. Improved structural performance in terms of material modifications, on the other hand, appears to lead to both sustainability (i.e., less embodied carbon materials) (Zaccaro et al., 2021; Nawi et al., 2018) and productivity (i.e., faster curating and hazardous resilient materials) directives (Gee and Brown, 2022).

However, recent economic contraction in the UK has raised concerns in respect of the adequacy of the adopted level of industrialisation, and its ability to meet the high expectations for the CI. Opoku and Mills (2019) argue that the current manufacturing scope falls short of realising broader the productivity benefits required to justify the new modes of operation, particularly through the standardisation of building components across multiple projects. By contrast, the Scandinavian, American, Australian and Japanese CI have embraced the standardisation of building manufacturing for more than a decade and has benefitted significantly. Studies by Anastasiades et al. (2021) and Steinhardt et al. (2019) extol the benefits of component standardisation for mass production of housing, and the opportunities for concurrent economies of scale and customisation. This highlights the missed opportunity for wider productivity gains for the UK CI, and the lack of comprehensive standardisation in building manufacturing. The adoption of standardised
components and platforms, as observed in Scandinavian countries, demonstrates the immense potential for increased efficiency and cost-effectiveness, which are only now being realised.

5.2 Process Performance Conduit

The OSC research into the process performance conduit has attempted to overcome the complexities in the supply chain through novel procurement methods and digital technologies. From the procurement-oriented perspective, a substantial amount of work has been undertaken in respect of managing the information flows amongst various actors in complex OSC supply chains. The early emphasis revolved around adopting standardised procurement strategies such as PFI and PPP, enabling clients to identify and integrate OSC components during the post-design completion (Pan et al., 2009). In contrast, the subsequent research endeavours have shifted towards design-oriented procurement strategies, exemplified by DfMA, enabling a comprehensive design approach to facilitate early identification of manufacturing and assembly stages related concerns (Charlston and Dimka, 2021; Banks et al., 2018). These methods have attempted to attain higher productivity and sustainability levels by minimising unnecessary delays and eradicating waste as a result of interoperability among supply chain actors (Pan et al., 2008; Stephenson and Kirkham, 2005).

Nevertheless, the research focus on procurement has paid minimal attention to an early design approach that considers the aftermath of building assembly.

Despite the growing interest in incorporating digital technologies into the OSC process performance, the current stage of integration remains in its nascent phase. The primary focus of research spins around the adoption of BIM, driven by UK government initiatives (Alwan et al., 2017). However, the integration with other emerging technologies seems limited in scope (Iacovidou et al., 2021). Moreover, the emphasis on BIM incorporation has primarily centred on managing design information, with insufficient attention to its applicability in manufacturing and assembly stages, as dictated by prevailing procurement strategies. The impact of digital technologies on UK OSC extends beyond information management, encompassing the control of physical OSC processes in factory settings. In this deposition, there is a notable emphasis on integrating robotic arms into manufacturing processes (Taylor, 2022) and leveraging the rapid manufacturing capabilities facilitated by 3D printing in controlled factory environments (Tobi et al., 2018).

However, certain aspects of robotic technologies, particularly unmanned aerial vehicles (UAV) and
automated guided vehicles (AGV) developed for on-site assembly, have encountered limited academic scrutiny within the UK (Brissi et al., 2022).

Figure 10. Three Primary Conduits: Causal Relationship Model

Where once the UK led the way with industry-wide procurement initiatives, international research demonstrates comparable developed nations are employing a more holistic approach to building lifecycles. Notably, studies by Harivardhini et al. (2017) and Peeters et al. (2017) go beyond DfMA, delving into building disassembly, evaluating environmental benefits, and embracing the ideals of the circular economy. Additionally, the adoption of digital twin technology has gained substantial momentum in other developed
nations (Yitmen et al., 2021), which stresses the need for the UK to acknowledge a dynamic digital representation that surpasses the static representation offered by BIM - underscoring a shift from viewing buildings as standalone assets and instead recognise their interconnectedness within an industry-wide supply chain. Also, the UK's OSC trajectory regarding digital technologies like robotics, UAVs, and UGVs is primarily fixed on improving manufacturing process performances within controlled factory environments. In contrast, developed economies like the USA and Scandinavia, as highlighted by Xiao et al. (2022), extend their focus to encompass efficient resource management and on-site assembly supervision through the integration of these technologies. This accentuates the necessity for the UK to broaden its digital focus beyond manufacturing processes, emphasising an industry-wide supply chain perspective.

5.3 Environmental Performance Conduit

Carbon emissions have increasingly become the primary focus for Environmental performance in OSC. Precedence has been placed on highlighting the environmental benefits relative to traditional construction practices (Monahan and Powell, 2011; Anderson et al., 2022). To effectively mitigate embodied and operational carbon emissions, several strategies and technologies have been introduced. These include the incorporation of principles from Passivhaus design (Rodrigues et al., 2016), energy retrofitting (Jankovic, 2019) and enhanced material specifications (Parker, 2013). It is noteworthy though, that while the included studies have acknowledged the importance of incorporating carbon emissions during the O&M stages, there has been limited consideration given to the subsequent phases, specifically the dismantling and potential re-use and/or recycling. As highlighted in previous discussions herein on performance themes, the CI is swiftly adopting the principles of the circular economy, this holds true for environmental performance as well, with the emphasis on reusing components in future supply chains (Mignacca and Locatelli, 2021). This paradigm shift towards circularity may ultimately require expanding the conventional scope of carbon assessments conducted in OSC-related research beyond the O&M stages.

The studies of Khan et al. (2022) and Wraslen et al. (2018) examined the embodied carbon estimation methods in the context of the USA, Norway, and Australia. Collectively, the findings of these studies reveal a striking similarity between these countries and the UK in terms of employing inventory-based carbon estimation approaches during the early design phase. However, as highlighted by Anderson et al. (2022), this method holds a level of uncertainty when it comes to accurately capturing the carbon emissions during
Therefore, it is imperative to recognise the pressing need for the development of more robust methodologies to accurately assess and mitigate the long-term carbon impacts of buildings.

**5.4 Future Research Directions**

The preceding discourse has shed light on the progressive trajectory of OSC research, delving into its structural, process, and environmental conduits. Taking an objective stance on the interconnections and interdependencies among these performance conduits, the authors propose the following recommendations to enhance OSC research (refer to Figure 11), with a focus on effectively navigating the intricate conundrum of balancing productivity and sustainability inherent in OSC.

**Figure 11: Future research directions for OSC research in the UK**

The progressive industrialisation of the building manufacturing process has propelled OSC as a means to enhance building structural performance. It is important to recognise however, that industrialisation also carries risks and presents vulnerabilities, in particularly towards health and safety regulations and workforce competencies. Therefore, future research must confront these concerns by evaluating the effectiveness of
various training and certification programs for the OSC workforce. Additionally, the exploration of emerging technologies such as augmented reality and virtual reality present opportunities to enhance worker safety and competency.

Process performance in OSC presents uncharted territory, particularly concerning the development of procurement strategies to alleviate supply chain issues and the integration of digital technologies. There remains an urgent need to develop innovative procurement methods capable of navigating the inherent complexity and variability within the OSC supply chain. In terms of digitalisation, BIM has gained widespread adoption, while the incorporation of other technologies remains limited. Therefore, future research endeavours must expand the scope of procurement and digitalisation to encompass the entire lifecycle of OSC, extending beyond the dismantling stage.

The early stages of a building's lifecycle have dominated research into environmental performance. To gain a more comprehensive understanding of OSC's environmental impact, future research must expand its analysis to encompass the entire OSC lifecycle. This expanded scope necessitates considering the environmental consequences of all processes and stakeholders involved in the building's lifecycle, including upstream and downstream activities such as raw material extraction, transportation, and recycling. Additionally, there is significant potential for research to explore the application of circular economy principles in OSC, with a specific focus on mitigating GHG emissions through the recycling and reutilisation of building components and materials.

Though the study investigates the sustainability narrative in the UK’s OSC evolution, the focus has been centred on environmental sustainability, warranting future research to encompass the interconnected dimensions of social and economic sustainability. Accordingly, acknowledging the prevailing social stigma against OSC in the UK due to misconceptions regarding quality and aesthetics is crucial. Likewise, OSC discourse in the UK has predominantly centred around economic efficiency, overlooking societal ramifications such as job creation and community engagement. This myopic focus risks overlooking OSC's social implications, potentially exacerbating inequalities and displacing traditional construction workers. Hence, future research and development endeavours should pivot towards a comprehensive approach addressing economic, environmental, and social sustainability. This entails not only enhancing OSC's economic viability but also scrutinising its societal impacts and rectifying existing stigmas through strategic
interventions. Reframing the narrative surrounding OSC to highlight its broader societal benefits is essential for fostering a more inclusive and sustainable built environment in the UK.

5.4.1 Need of a ‘Holistic Integrated Thinking’ strategy to address CI challenges

In view of the future research directions pertaining to all three performance conduits, it is imperative to expand current research and potential future endeavours with a concerted emphasis on overlapping focus areas. This necessitates the adoption of Holistic Integrated Thinking (HIT) that comprehends the interrelated impacts of the three conduits. Holistic thinking emphasises perceiving all facets of a situation as an indivisible whole. In the OSC context, this entails recognising the interconnectedness of structural, process, and environmental conduits without a compartmentalisation (Harrison, 2008). Integrated thinking, on other hand, directs industries to address the diverse needs of specific performance conduits through harmonising efforts across stakeholders in the OSC supply chain (Maroun et al., 2023). Accordingly, this study promotes the HIT as a unified strategy that addresses the entire OSC lifecycle, from procurement and digitalisation to environmental impact, ensuring a balanced and cohesive approach. Focusing solely on one element without acknowledging and addressing its relationship to the rest of the conduits offers little (i.e., subjective) to inform and advance the CI. The existence of longstanding fragmentation in the CI continues, but these findings and insight present an opportunity for significant change. While these performance conduits may initially appear disparate, it is contended that bringing these conduits together could help identifying their interconnectedness. Additionally, such synergy between conduits has the potential to create opportunities that leverage the strengths of each performance conduit while overcoming their respective weaknesses. Ultimately, this approach should help promote progress and innovation across the entire CI, regardless of its geopolitical context.

6.0 Conclusion and Way Forward

Over the last 20 years, the trajectory of OSC in the UK has evolved significantly, transitioning from emphasis on augmenting productivity through enhancements in structural and process performance, to one which is more aligned to environmental sensitivity. Whilst industry fragmentation continues to stifle progress, evidence suggests that OSC is now starting to acts as a coalescing stabiliser through common purpose in order to achieve productivity and sustainability goals more purposefully. Industry analysis on
OSC and the CI’s dynamics revealed the need to engage a more integrated (formalised) way of embracing OSC productivity and sustainability.

This research highlighted three performance themes: (i) structural, (ii) process, and (ii) environmental as the main observational research lens. Whilst acknowledging overlapping inferences, collectively, it was posited that these overlaps would help provide a richer and more insightful view of OSC’s influence on the CI. One of the challenges was to scrutinise the extent to which OSC contributed to the realisation of the CI-wide sustainability objectives. In this respect, comparative analysis was used to assess the ‘status-quo’ of each performance theme within the UK CI compared to other developed countries of similar standing with OSC. From this, a causal relationship model was developed to highlight current and future trajectories.

Findings from this revealed that despite numerous initiatives aimed to improve the UK’s OSC’s sustainability accountability, that some of these did not seem to meet expectations, thereby fell short of performance levels exhibited by others in similar developed countries. Notably, that UK OSC research had predominantly focused on ‘silied solutions’ rather than adopting a more cohesive (integrative) approach.

In recognition of this, it is important to acknowledge that the identification of these divisions (and interplay forces), were pivotal for uncovering specific challenges and subsequent alignment pathways needed for promoting success. In this respect, findings from this OSC research revealed an expansion within functional boundaries; yet this in itself (in isolation) lacked cohesion with interconnected studies and seminal literature. Consequently, it was argued that there was a need for "Holistic Integrated Thinking" - a strategic blend of holistic and integrated approaches. Holistic thinking emphasises the need for a wider comprehensive view, one which considers all interconnected elements and non-tangible factors. Integrated thinking, on the other hand, focuses on unifying diverse perspectives within a specific context (Harrison, 2008). Thereby, the proposed HIT strategy (presented in this paper) harmonised these two approaches in order to provide a more conjoined and cohesive understanding of OSC sustainability intersections.

Moreover, from an OSC research perspective, HIT can be seen as a novel approach – one which reinforces the need to streamline causal forces, interconnections, and dependencies through formalised structures. In doing so, then this could also be used to leverage the collective intelligence of the UK CI sector (and wider thinking) to support global success.
The three primary conduits presented in the causal relationship model can be considered a first step in establishing the “collective intelligence” needed to make more considered and informed decisions. In this respect, from a generalisability and repeatability perspective, it should be formally acknowledged that this model is context-bound to UK-specific data set anchors and concomitant axial coding approaches; and that any form of subsequent replication, propagation or inference (beyond this boundary) should recognise this.

The three primary conduits emanating from this study contributes to theory development in two main areas: (i) Constructivism Learning theory, by identifying the factors that engage the active role of OSC actors to build their own understanding (and collective understanding) through reflection/experience in order to promote a much deeper understanding of how to achieve better integrated ways of embracing productivity and sustainability through OSC solutions; and (ii) Organisational theory, where findings promote the need to “strike a balance” between contested areas; this includes the need to change the behaviour of both individual actors (micro forces), and the concomitant OSC organisations and infrastructure (macro forces) in order to better support SDG goals.

The outcomes of this study align with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 9, which focuses on Industry, Innovation, and Infrastructure, and SDG 11, addressing Sustainable Cities and Communities. The research directions advocate for a HIT strategy to address challenges within the CI, aligning with the collaborative ethos of SDG 17 (Partnerships for Goals). The study’s emphasis on achieving a balance between productivity and sustainability aligns seamlessly with the objectives of SDG 12 (Responsible Consumption and Production). In essence, this research provides a strategic trajectory for the UK CI to positively impact global sustainability aspirations, with potential future directions highlighting the intersection between OSC and SDGs, specifically in the context of environmental performance in the UK.

Finally, whilst this work presented a thematic nuanced account of the evolution of OSC and future pathways needed for research/practice through the HIT strategy; equally, there is a much wider need to examine these issues further in order to “strike a balance” between productivity and sustainability (rather than prioritising one at the expense of the other). Where for example, the use of pathway and co-dependency/enmeshment analytical approaches could be used to develop future understanding of these complex interconnected issues.
References


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