Evaluation of lean off-site construction literature through the lens of Industry 4.0 and 5.0

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Abstract

Lean manufacturing principles are being increasingly employed in off-site construction (OSC), with the primary objective to reduce waste and improve production efficiency. This is performed using several tools and technologies largely influenced by the concept of Industry 4.0 (I4.0) which sets fundamental design principles for technological development. However, the recent introduction of the concept of Industry 5.0 (I5.0) extends I4.0 focus towards wider economic, social, and environmental implications. This study aims to evaluate extant literature employing lean tools and concepts in OSC towards the realisation of I4.0 and I5.0 design principles, identifying key research themes and gaps and suggesting future directions. A mixed method review was employed to firstly identify highly relevant literature using bibliometric search. The identified references were then analysed using qualitative content analysis through the lens of I4.0 and I5.0. Results highlight several interactions between identified lean-OSC tools and concepts, and I4.0 and I5.0 design principles, signifying the power of these tools/concepts in meeting multiple industry objectives. The review also identifies significant overlap between resilience principle in I5.0 and many of I4.0 principles, emphasising resilience as an integrative concept of technological principles. Finally, several research gaps relating to the social and environmental aspects of lean-OSC research were identified, including research on mental health, assistive technologies, and design for end-of-life.

Author Keywords: Off-site construction; Lean manufacturing; Industry 4.0; Industry 5.0; Bibliometric search; Mixed method review.

Practical Applications

Practitioners can benefit from understanding the capabilities of lean-OSC tools, such as process simulation and BIM, in addressing a wide range of design principles of I4.0 and I5.0. This paper also identifies the importance of exploring underexplored themes in the literature, particularly the mental health of workers in off-site construction environments. As the industry continues to evolve, construction professionals should consider incorporating new technologies and methodologies to monitor and support the mental well-being of their workforce. There is significant potential for improvement in adopting human-centred technologies, like collaborative robots and exoskeletons, which can empower workers and enhance workplace diversity and inclusion. This involves exploring innovative technologies that facilitate cross-lingual communication, gestures recognition, and intention prediction, providing opportunities for individuals with different languages, education levels, and disabilities to participate effectively. Furthermore, the research highlights the need to concentrate on environmental sustainability, specifically the integration of circular economy concepts into off-site construction practices. By examining the potential of lean principles in promoting end-of-life design considerations, such as design for disassembly and material passports, construction professionals can bridge the gap between OSC and circular economy concepts, creating a more sustainable construction industry.

Introduction

The construction industry has long been identified with the need to improve its productivity and performance. One major attribute behind the lack of industrial growth is the traditional stick-built approach, which is characterised with low standardisation, high fragmentation, and limited automation (Li et al. 2014). These inefficiencies are not only associated with economic disadvantages, but also with significant environmental impacts. For instance, the industry contributes globally 40% solid waste (Oluleye et al. 2022), 33% greenhouse gasses emissions, and 40% energy consumption (Ouldboukhitine et al. 2011).

In response, various governments promotes the adoption of off-site construction (OSC) as a more sustainable building technique with promising capabilities to enhance productivity and reduce environmental footprints (Jin et al. 2018). Typically, it involves the production of building modules as components (e.g., wall panels or pods) in a factory setting before they are transported to construction sites for installation (Goodier and Gibb 2007). The factory production environment in OSC has long motivated academics and practitioners to apply proven manufacturing techniques to increase productivity and profitability. OSC is suggested to create several economic, social, and environmental benefits, including reduced construction time (Mostafa et al. 2016), improved building quality (Zabihi et al. 2013), enhanced health and safety (Mohandes et al. 2022), reduced construction waste (Mirshekarlou et al. 2021), improved resource utilisation (Kedir and Hall 2021), and decreased carbon emissions (Wang et al. 2022).

Lean manufacturing is a major production philosophy, originally developed by Toyota for automobile production (Ohno and Bodek 1988). The main objective of lean philosophy is to maximise customer value while reducing waste (Lean Enterprise Institute 2022). Given its significant potential to improve efficiency and reduce waste, there is a growing body of research employing lean principles to enhance OSC operations. This includes the use of just-in-time (JIT) to optimise production efficiency (Afifi et al. 2020), visual management to monitor and control the assembly process (Ma and Qiao 2021), Kaizen (i.e. continuous improvement through measures adopting lean principles such as understanding customers, empowering people and keeping the system transparent, etc.) to improve manufacturing productivity (Darwish et al. 2020), and value stream mapping (VSM) to reduce lead times (Zhang et al. 2020).

While majority of literature on lean off-site construction or lean manufacturing in off-site construction (referred as ‘lean-OSC’ hereafter) emphasises the economic benefits, there are relatively fewer studies focus on the wider social and environmental implications of lean-OSC. Some researchers attribute this imbalance to the over-emphasis of the use of digital technology in achieving economic gains as the industry is going through the fourth phase of industrial revolution, i.e. Industry 4.0 (I4.0) (Xu et al. 2021). Recently, a new phase known as Industry 5.0 (I5.0) was proposed in attempt to steer a balance by focusing on wider social and environmental benefits that go beyond just growth and productivity (Breque et al. 2021). Given the growing uptake of lean theory in OSC and the ever-evolving industry requirements, our knowledge is limited on how the application of lean tools and concepts in OSC can contribute to the realisation of I4.0 and I5.0 principles. The authors conducted a thorough search but could not find any prior studies that evaluated the potentials of lean in OSC towards meeting I4.0 and I5.0 principles, widely recognized as important targets for several economies around the globe.

This study aims to evaluate extant lean-OSC literature in the lens of I4.0 and I5.0 conceptualisations, identifying key literature themes and gaps, and suggesting direction for future research. To realise the study aim, the design principles underlying I4.0 and I5.0 are reviewed and summarised. These principles are then used for evaluating the lean-OSC literature. A mixed method review is adopted comprising the use of a bibliometric search to objectively identify the research networks in lean-OSC literature which act as the main input to a qualitative content analysis to evaluate the literature from the perspective of I4.0 and I5.0 design principles.

There are several published reviews amongst existing OSC literature addressing different aspects in theory and practice. This includes reviews on OSC environmental sustainability (Chen et al. 2022; Kedir and Hall 2021; Li et al. 2022; Luo et al. 2021; Zairul 2021), structural integrity (Ghayeb et al. 2020; Navaratnam et al. 2019; Thai et al. 2020; Ye et al. 2021), supply chain management (Hu and Chong 2021; Hussein et al. 2021; Masood et al. 2022; Wang et al. 2019), health and safety (Nguyen et al. 2020; Vithanage et al. 2022), and digital technology (Assaf et al. 2022; Pan et al. 2022; Pasco et al. 2022; Qi et al. 2021; Wang et al. 2020b). Although these reviews offered comprehensive analysis on different sustainability dimensions, such as carbon reduction, circularity, and safety, links to lean uptake in OSC were not clear. Only few reviews focused on the interplay between OSC and lean principles, studying key literature directions, such as system automation (Gusmao Brissi et al. 2022), process simulation (Daniel and Oshodi 2022; Mostafa et al. 2016), lean applicability (Du et al. 2023; Innella et al. 2019), and critical success factors (Hussein and Zayed 2021). However, these reviews have not fully addressed the theoretical dimensions of I4.0 and 5.0, leaving a theoretical void that requires scholarly attention. That is, little is known on how lean tools and concepts can facilitate the realisation of I4.0 or I5.0 design principles in OSC. Furthermore, these reviews mostly adopted a manual approach in selecting relevant references. While they all have a clear set of selection criteria for selecting articles that allows the authors to study the contents of articles in-depth according to their angle adopted for evaluation, there is an element of subjectivity for interpretation of their criteria used, which can be prone to selectivity and lack of replicability (Hammersley 2001). Improving from the previous reviews, this study employs a mixed method attempting to benefit from the quantitative powers offered by the adopted bibliometric search to shield potential authors' selectivity as well as an in-depth qualitative content analysis. Thus, the literature analysis and evaluation are arguably more objective (see Hosseini et al., 2018). Moreover, our study is limited to reviewing empirical studies, which are accentuated by several scholars (e.g., Bhamu and Sangwan, 2014) to enhance the theoretical base of reviews.

This review contributes to existing body of knowledge in several ways. First, it informs OSC theory and practice with the capabilities of applied lean tools and concepts in fulfilling different industry requirements, including technological, economic, social, and environmental. In addition, our study identifies key research gaps extant lean-OSC literature did not address fully in the light of I4.0 and I5.0 design principles. In doing so, significant research directions are suggested for future research to address.

Industry 4.0 & 5.0 design principles

Coined in 2011 by the German Federal government as part of a technological strategy, I4.0 theorised the reliance on Cyber Physical Production Systems (CPPSs) (Vogel-Heuser and Hess 2016). CPPSs offer smart and timely decisions communicated across the production infrastructure (Lu et al. 2020), leading to significant improvements in product quality, process lead times, and production efficiency (Zhong et al. 2017). To achieve I4.0, there are design principles identified to enable manufacturers to conceive the transformative trends in the industry and update their strategies accordingly (Ghobakhloo 2020). The most prevalent categorisation to I4.0 design principles across the literature includes interoperability, virtualisation, decentralisation, real-time capability, service orientation, and modularity (Koh et al. 2019; Lu 2017; Mrugalska and Wyrwicka 2017; Oztemel and Gursev 2020; Shafiq et al. 2015, 2016; Wulfsberg 2017).

Although a few studies mentioned additional I4.0 design principles to address social and environmental issues, such as social responsibility (Ghobakhloo 2018) and resource efficiency (Kagermann et al. 2013), I4.0 is criticised for putting excessive focus on technologies to realise economic gains (Xu et al. 2021). The technology driven transformations brought by I4.0 is blamed for limiting human intervention (Demir et al. 2019; Lasi et al. 2014) and overshadowing environmental protection principles (Maddikunta et al. 2022).

In response, I5.0 has been recently introduced with the aim of achieving wider production value beyond growth and profitability (Breque et al. 2021). The European Commission through its Directorate-General for Research and Innovation formally presented the concept in 2021 (Xu et al. 2021). According to the European Commission, "*industry 5.0 recognises the power of industry to achieve societal goals beyond jobs and growth to become a resilient provider of prosperity, by making production respect the boundaries of our planet and placing the wellbeing of the industry worker at the centre of the production process*" (Breque et al., 2021; p.14). I5.0 therefore prioritises human-centricity, environmental sustainability, and resilience as major design principles. I5.0, however, shall not be seen as a chronological continuation of I4.0 (Xu et al. 2021). Rather, it is viewed as a complementary concept, emphasising wider social and environmental implications (Breque et al. 2021). Table 1 summarises the definition for each of I4.0 and I5.0 design principles. This study adopts those design principles as a theoretical lens to evaluate lean-OSC literature later in this paper (see Qualitative Evaluation Section).

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Methodology

The aim of this study is to evaluate lean-OSC literature through the lens of I4.0 and I5.0 design principles, identifying major literature themes and gaps, and suggesting future research direction. To achieve this aim, a mixed method review was pursued starting with quantitative bibliometric search to identify extant lean-OSC literature, followed by a qualitative content analysis to evaluate identified studies from I4.0 and I5.0 perspectives. The bibliometric approach provides objective criteria to identify the literature, through which the qualitative approach goes on to offer more detailed synthesis on the relations, connections, and gaps (Harden and Thomas 2015).

Two major keywords were used in the bibliometric search, namely: *off-site construction* and *lean*. Interchangeable, synonymous, and related terms for the major keywords were identified to make sure that the search is as comprehensive as possible. Upon reviewing key reviews in the field (e.g., Jin et al., 2018; Yin et al., 2019), a range of synonymous and associated keywords were identified and included in the search term as shown in Table 2.

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Scopus database was chosen to search the articles for the analysis as it covers a wide range of research publications (Chadegani et al. 2013; Darko et al. 2020), particularly in the field of construction management (Hosseini et al. 2018; Yin et al. 2019). Based on the keywords defined in Table 2, 586 articles were firstly retrieved. They were further reduced to 394 after 1) filtering out research in languages other than English, 2) excluding irrelevant subjects (e.g. medicine, agriculture), 3) excluding reviews and 4) setting the search period to the last 15 years - as I4.0 was introduced in 2011 and there is a notable drop in the number of publications relevant to the keywords in 2007 and before (See Figure 1).

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Bibliometric search (introduced in the next section) was then employed to identify research networks in the field of lean-OSC. The analysis identified one major research network and eight minor ones, totalling 98 publications out of the 394 identified studies in the manual search. Content analysis, introduced in the Quantitative Evaluation Section, was then performed to firstly identify highly relevant papers to the study aim, bringing the total number of publications down to 61. Theoretical and opinion-based articles were mostly excluded while more focus was given to empirical research to ensure that our findings are based on evidence rather than abstract theories. This is followed by literature evaluation to assess the 61 publications in the lens of I4.0 and I5.0 design principles. Figure 2 summarises the research design pursued in this paper.

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Bibliometric search

VOSviewer was adopted for the bibliometric search as a widely utilised software and as an efficient distance-based visualisation tool for research authorship, sources, keywords, and articles compared to other bibliometric analysis tools, such as CiteSpace and CiteNetExplorer (Yin et al. 2019). However, the adopted bibliometric search in this study is not meant to analyse the retrieved literature sample (the 394 articles) in terms of their bibliometric information (e.g., authors, countries, trends). Instead, it is intended to objectively identify the research networks in the field of lean-OSC and so providing content analysis with highly relevant studies to be evaluated from I4.0 and I5.0 perspectives.

Particularly, articles citation analysis is adopted to 1) help identify lean-OSC research networks more precisely based on relevant citations of recent articles to former ones; and 2) exclude irrelevant and low quality/contribution papers which typically appear isolated with no single link (i.e., citation) to the networks. We did not use bibliographic coupling analysis since it prioritises research based on shared citations across the retrieved literature sample (i.e., the 394 articles) (Van Eck and Waltman 2021), no matter their relevance or contribution to the research niche. In addition, threshold setting at bibliographic coupling analysis is arbitrary, based on mutual citations that can lead to potential exclusion of relevant research. Therefore, a lower threshold is preferred but considered impractical due to the significant number of research that typically results in, requiring excessive screening effort. By contrast, at articles citation analysis, a threshold of zero citations can be adopted to include all relevant research to the research niche.

Based on articles citation analysis, the data of the 394 publications, initially mined from Scopus database (see Method Section), was fed into VOSviewer. A threshold of zero citations was set, since the main value of using the bibliometric search in this study is to identify the research networks, not the most significant publications. This threshold then allowed including potentially recent publications that have not yet received citations but cited previous work in the networks. VOSviewer afterwards identified one major research network with 79 publications (Figure 3) and eight minor networks with 2-4 publications each (Figure 4). In total, VOSviewer visualised 98 publications in all networks, while the rest of the 394 publications appeared isolated, signifying potential irrelevance or limited contribution to lean-OSC research. The authors investigated filtered research and found that a significant number of articles was irrelevant, initially included because of keywords similarity to other disciplines (e.g., computer science, astronomy). In comparison, fewer excluded studies are found to be relevant. Although these studies received citations in general, they fail to receive or make a single citation to the research network that is highly relevant to the research niche. As a result, this research appeared isolated, without any connection to the VOSviewer research networks. Although the content of the research may seem relevant, we considered it to have a low contribution because it is not well embedded in the literature under investigation. Hence, the value of these networks is to filter out less relevant studies to the research aim, allowing us to focus further qualitative analysis on more relevant and coherent body of research.

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Figures 3 illustrates the biggest network of identified research (79 publications) in the field of lean-OSC using VOSviewer articles citation analysis. Minor networks of such studies were also identified (19 publications) as shown in Figure 4. The size of the node represents the number of total citations received by each publication (in general). The bigger the node is, the more citations received by the study. The links between nodes indicate the citations of recent studies to former articles. The more links connected to a single node, the more relevant citations are made to the given study in that node. The main purpose of this study is to evaluate the literature from I4.0 and I5.0 perspectives, not to define literature themes and patterns. The major function of the bibliometric search is to identify lean-OSC research networks (i.e., connected by citations) and so provide content analysis with an objectively identified literature sample to be evaluated in the lens of I4.0 and I5.0 design principles.

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Qualitative evaluation in lens of I4.0 & I5.0

Content analysis was then employed to identify and analyse the most significant studies to the research aim. As clarified in the Method Section, only empirical studies are selected for further analysis, while theoretical and opinion-based studies are excluded to ensure that our review is based on evidence, rather than theories. The number of studies was therefore reduced down to 61 articles (see the Appendix), as a major input for literature evaluation. Based on the definitions introduced earlier in this review, literature evaluation in the lens of I4.0 & I5.0 design principles were performed as outlined in the below subsections.

Interoperability

The Internet of things (IoT) is the key enabling technology underpinning I4.0. One challenge for IoT to operate efficiently and effectively is the need for systems to exchange, integrate and use information seamlessly or in other words, systems need to be interoperable. Interoperability, thus, refers to the ability of different systems to exchange, integrate, and utilise data to enhance information sharing and exchange (Lu 2017).

Interoperability can be classified in four progressive levels (Van Der Veer and Wiles 2008), they are: 1) technical, to establish required infrastructure to share raw data, 2) syntactic, to share compatible data and offer minimal interpretation, 3) semantic, to exchange and interpret data to create shared meaning, 4) organisational, to share higher level of knowledge reflecting the efficiency of inter-organisational communications. The literature has mainly focused on syntactic and organisational levels.

For *syntactic interoperability*, several studies employed optimisation methods to orchestrate schedule trade-offs between the factory and the site, synchronising and prioritising data of several variables, including the selection of suppliers (Zhang and Yu 2020), late/early delivery penalties (Kong et al. 2018), and risk-related rescheduling options (Du et al. 2022). Other studies adopted cross process simulations to integrate information of different processes to optimise total time and cost (Heravi et al. 2021), carbon emissions (Heravi et al. 2020), and digitalisation efficiency (Barkokebas et al. 2021a). Further, takt planning is employed to synchronise production information necessary to smooth resource utilisation (Chauhan et al. 2018), and reduce delays (Lerche et al. 2022). Other studies adopted Design for Manufacture and Assembly (DfMA) principles to synchronise design information with manufacturing and assembly processes to verify design geometry prior to production (He et al. 2021), and improve site safety and logistics efficiency (Banks et al. 2018). Therefore, these studies do not go beyond syntactic interoperability, failing to develop ontology-based systems, similar to those found in non-lean OSC literature on cost estimation (Vakaj et al. 2023) and manufacturability (Cao et al. 2022).

For *organisational interoperability*, several studies employed 4D BIM, a schedule visualisation tool integrating schedule and design information, to coordinate logistics and assembly activities among different project participants (Bortolini et al. 2019). Several benefits are reported by this literature, including improvements in transportation reliability (Bataglin et al. 2020), assembly control (Peñaloza et al. 2016), process transparency (Bataglin et al. 2017), and schedule compliance (Wang et al. 2020a). Other studies developed a range mass customisation platforms that promote design collaboration (Jansson et al. 2014) by integrating the requirements of different stakeholders (Yazdi et al. 2020), particularly customer needs and expectations (Viana et al. 2017).

Virtualisation

Virtualisation principle aims to digitise physical systems to predict and optimise performance (Qi and Tao 2018). It can be classified to two categories 1) process level, to monitor and optimise process activities without disrupting physical world (Gilchrist 2016), and 2) product level, to have a holistic virtual view of a product from design to the end of life (Ghobakhloo 2018). For *process virtualisation*, several studies adopted process simulation techniques to optimise specific production sub-processes based on the lean concept of VSM. Typically, VSM is used to map and classify process activities into value adding, non-value adding, necessary non-value adding activities (Nikakhtar et al. 2015), before eliminating non-value adding activities (i.e., waste) to enhance process flow (Innella et al. 2019). Through process simulations to map current state activities, potential improvements are identified to enhance manufacturing productivity (Yu et al. 2013; Zhang et al. 2020), decrease lead times (Laika et al., 2022), optimise resource utilisation (Goh and Goh 2019), minimise cost (Heravi and Firoozi 2017; Laika et al. 2022), and reduce process waste (Ayinla et al., 2022; El Sakka et al., 2016). Other studies approached process virtualisation using simulations of workers motion and interaction primarily to reduce health and safety hazards. This includes the use of rapid entire body assessment (Ritter et al. 2019), and rapid upper limb assessment (Barkokebas et al. 2021b) to evaluate ergonomic risks and in turn enhance OSC health and safety conditions.

For *product virtualisation*, literature investigations approached it primarily in two different ways. The first involves the use of BIM to visualise progress in building construction (e.g., Bataglin et al., 2020; Peñaloza et al., 2016), facilitate module production (He et al. 2021), and optimise module assembly (Gbadamosi et al. 2019). Other studies adopted life cycle assessment (LCA) to estimate the environmental impacts of prefabricated components (Heravi et al. 2020) and their assembly stations (Kurdve et al. 2018). The importance of estimating the environmental impacts of OSC modules lies on the capability to control the footprint of contributing processes (e.g., production, logistics).

Decentralisation

The decentralisation principle aims to enable stakeholders and information systems to analyse data and take decisions independently in pursuit of common organisational objectives (Gilchrist 2016). The literature on decentralisation can be classified into 1) autonomous teams and 2) autonomous systems. For *autonomous teams*, several studies (e.g., Bataglin et al., 2020; Bortolini et al., 2019; Peñaloza et al., 2016) adopted Last Planner System (LPS) to achieve efficient delegation and collaboration in the planning and control of OSC operations. LPS is centred on the empowerment of people involved in planning and implementation of daily activities (Lean Construction Institute 2022).

For *autonomous systems*, several studies focused on developing optimisation-based models to facilitate decision making by optimising different supply chain variables, such as level of components modularity (Isaac et al. 2014), production sequencing (Arashpour et al. 2016), and logistics operations (Zhang and Yu 2020). Hu et al. (2021) hold that the quality of problem formulation highly influences the capability of optimisation models to establish a fully optimised and automated systems. Other studies used mass customisation platforms to promote design automation by identifying advanced capabilities to support handling unique designs (Jansson et al. 2014), defining rules and constraints for automated modules connections (Thajudeen et al. 2020), and adapting suppliers’ processes to platform requirements (Yazdi et al. 2020).

Real-time capability

Real-time capability refers to the quality in collecting, sharing, and interpreting data to assist timely decision making (Hermann et al. 2016). Based on literature analysis, three categories can be identified: design integration, production monitoring, and logistics tracking & control. Regarding *design integration,* BIM models form a reliable reference for decision making throughout construction lifecycle (National BIM Standard 2022). They can be integrated to other systems to verify production geometry (He et al. 2021) and develop mass-customisation platform (Thajudeen et al. 2020). For *production monitoring*, real-time process simulation is adopted using continuous event simulation to monitor production performance and device improvements in productivity (Afifi et al. 2020) and long-term efficiency (Arashpour et al. 2015). Real-time production monitoring systems facilitate proactive detection of process waste and so stimulate timely mitigating decisions (Snatkin et al. 2013). Other studies used the lean concept of takt planning to synchronise production rhythm with actual market demand, reporting several benefits including resource optimisation (Chauhan et al. 2018) and productivity improvements (Lerche et al. 2022). For *logistics tracking & control*, component level data (e.g., location and class) are synchronised in real-time using module tracking technologies, such as RFID and IoT to optimise logistics cost and efficiency (Wang et al. 2020a), and support on-time deliveries (Xu et al. 2018).

Service orientation

This principle aims to focus intelligent production systems on meeting or exceeding customer's needs and expectations (Kamble et al. 2018). The literature addressing this principle can be classified to production process and design process. The major portion of these studies focused on the *production process* using the concept of VSM to maximise customer value. Several studies (e.g., Heravi and Firoozi, 2017; Zhang et al., 2020) employed the lean concept of VSM with process simulation mainly to fast-track delivery by reducing lead times. Integrating VSM with discrete event simulations are widely advocated to model variability in customer demand, which otherwise the VSM per se is unable to model (Jarkko et al. 2013) due to its deterministic nature (Hampson 1999). Other studies adopted the lean concept of takt planning to match the production pace with actual customer demand and so promote resource efficiency and eliminate wasteful activities (Chauhan et al. 2018; Lerche et al. 2022).

Other studies (Jansson et al. 2014; Thajudeen et al. 2020; Viana et al. 2017; Yazdi et al. 2020) focus on the potentials of the *design process* in satisfying customer needs and expectation using mass customisation platforms. Mass customisation refers to the capability to deliver products that meet customers personalisation needs at mass production efficiency (MacCarthy et al. 2003). Hence, it attempts to realise two apparently conflicting objectives of high product variety and high volume (Viana et al. 2017). This capability is underpinned by two lean concepts: batch size reduction to promote design modularisation by dividing the building design into smaller common modules (Hopp and Spearman 2004), and standardisation to consolidate module design with the aim of realising mass production efficiency (Liker 2020).

Modularity

This principle enables supply chain to adopt agile mindset in responding to rapidly changing market conditions (Ghobakhloo 2018). Based on the analysed literature, two major categories are identified, namely product-based and process-based modularity, both concentrating on breaking the major module/system into smaller manageable units (Koh et al. 2019). Focusing on *product modularity,* several studies (Choi et al. 2020; Feist et al. 2022; O’Connor et al. 2015; Økland et al. 2017, 2018; Viana et al. 2017) adopted design modularisation to enhance post-design modules identification (Feist et al. 2022), decrease cost, delays and defects (Økland et al. 2017, 2018), and reduce complexity in engineer-to-order projects (Viana et al. 2017). Other studies focused on DfMA aiming at product design simplification and integration to enhance manufacturability and constructability (Leminen et al. 2013). This includes the development of design modularisation tools to assess module design based on the level of modularity, standardisation, producibility, and assembility (Antoniou and Marinelli 2020; Gbadamosi et al. 2019).

Several other studies focused on *process modularity*, with primary adoption of process simulation to map and optimise specific production processes. Applying the lean concepts, these studies demonstrate a range of benefits in productivity (Yu et al. 2013), lead time (Heravi and Firoozi 2017), and resource efficiency (El Sakka et al. 2016). In addition, there are studies adopting the concept of flying factories to physically modularise specific production activities on site (He et al. 2021; Martínez et al. 2013; Rosarius and García De Soto 2021), demonstrating a number of economic, social, and environmental benefits.

Human centricity

This principle involves prioritising workers' needs and interests over growth and profitability brought by emergent technologies (Nahavandi 2019). The *empowerment of people* is identified as the major aspect emphasised by this literature, mainly underpinned by the lean concept Kaizen, to eliminate process waste (El Sakka et al. 2016), boost productivity (Afifi et al. 2020), and reduce lead times (Barkokebas et al. 2021a). Kaizen refers to the labour-led continuous improvement mindset to remove waste and enhance process efficiency (Nahmens and Ikuma 2012). Other studies suggest cross-training to expand multi-skilled labour, reporting improvements in changeover times (Arashpour et al. 2016), labour utilisation, and productivity (Arashpour et al. 2017; Goh and Goh 2019). Multi-skilled workers, for instance, can improve production flexibility by addressing potential variabilities in resource availability and customer demand (Alvanchi et al. 2012). Andersen et al. (2008) suggest the social infrastructure (e.g., shared vision & internal coherence) underpinning OSC production culture as a prerequisite for successful manufacturing environment. This view is reinforced by Alazzaz and Whyte (2015) who revealed a significant positive correlation between labour empowerment and productivity in OSC.

Labours' *health and safety* is another aspect researched by several studies, using a range of tools and techniques. I5.0 introduces workers' health and safety as an essential requirement, aiming at enhancing physical health, mental health, and wellbeing (Xu et al. 2021). Relevant literature includes the adoption of Kaizen to encourage workers' led safety improvements (Nahmens and Ikuma 2012), ergonomic risk assessment to evaluate proposed process improvements (Barkokebas et al. 2021b; Ritter et al. 2019), and JIT to reduce site hazards related excess inventory (Court et al. 2009).

There are studies promoted *wider social implications* to OSC, as a core tenet of I5.0, which postulates that technology has to be designed to serve the wider community, not the opposite (Breque et al. 2021). Particularly, employment prospects are promoted by some studies adopting the development of less skill-demanding production technologies based on the lean concept of poka-yoke (i.e., error proofing) to enhance the quality and safety of manual assembly activities (Kurdve 2018; Kurdve et al. 2018). Likewise, flying factories are being recommended as an efficient way to enhance local labour employment, combining the advantages of off-site and on-site construction (Li et al. 2020).

Environmental sustainability

Sustainability principle aims to reduce waste, minimise environmental impacts, and promote circular manufacturing principles (Rada 2018). The analysis reveals three major interrelated foci under this principle, including waste reduction, emissions cut, and circularity promotion. For *waste reduction*, a significant number of studies adopt process simulations to reduce process waste, including the reduction of overproduced modules (El Sakka et al. 2016), lead times (Heravi and Firoozi 2017), and work-in-progress levels (Goh and Goh 2019). Process waste refers to the excess amount of production resources that do not add customer value (Ayinla et al., 2022). These waste are directly and indirectly linked to the generation of solid waste, which creates negative environmental impacts (Nahmens and Ikuma 2012). Several studies identified the potential of OSC in reducing material waste by improving production accuracy (He et al. 2021), optimising design to facilitate assembly (Gbadamosi et al. 2019), and devising process improvement to reduce off-cuts (Nahmens and Ikuma 2012).

For *emissions reduction*, several studies promoted reducing logistics emissions resulting from transporting building modules from OSC facilities to the site. This includes literature adopting JIT to optimise transportation time and quantity (Kong et al. 2018), DfMA to enhance transportation efficiency (Banks et al. 2018), and flying factories to eliminate factory-to-site transportation (He et al. 2021). Other studies employed LCA to estimate material emissions as a result of raw materials' extraction, transportation, processing, construction, renovation, maintenance, deconstruction, and disposal, i.e. their embodied carbon emissions. Kurdve et al. (2018), in a case study, adopted LCA to carry out emissions hotspot analysis that assist designers to choose environmentally friendly materials in early design stage.

Mignacca and Locatelli (2021) stress the need to overcome barriers in the face of modular circular economy which involves the building strategy where prefabricated modules are designed to be reused, maintained, altered, and recycled (Mignacca et al. 2020). For *circularity promotion*, the literature focused on the reuse of shipping containers in construction as building modules. This includes the work Giriunas et al. (2012) who investigated the structural capabilities of shipping containers using finite element analysis, producing a structural guidelines for reuse in construction. Relatedly, Su et al. (2022) used BIM to integrate data on shipping containers and traditional construction modules to promote their reuse in construction. The reutilisation of shipping containers in construction is gaining popularity as a modular circular building technique, e.g., the Stadium 974 project in Qatar that uses 974 recycled shipping containers to build a football stadium.

Resilience

This principle aims to establish higher levels of production robustness mainly to withstand potential supply chain disruptions (Breque et al. 2021). Ekanayake's et al. (2020) define nine components for OSC supply chain resilience, including resourcefulness, flexibility, capacity, adaptability, efficiency, financial strength, visibility, anticipation, and dispersion. The authors also identify a range of supporting traits for each component (see Table 6). Most of those traits are arguably applied to some of the I4.0 design principles, e.g. “collaborative information exchange and decision making” for interoperability, “modular product design” for modularity, “products, assets, people visibility” for virtualisation, “monitoring early warning signals” and real-time capability, and “distributed decision making” for decentralisation.

Other studies promoted several resilience traits in different components with no direct link to I4.0 design principles. For example, studies promoting OSC health & safety (e.g., Barkokebas et al., 2021b) supported “resourcefulness” component since they aim to reduce disruptions related to labour health & safety (Ekanayake et al. 2020). Likewise, studies adopting JIT (e.g., Kong et al., 2018) and standardisation (e.g., Antoniou and Marinelli, 2020) supported “flexibility” component, since they both facilitate timely and efficient resource mobilisation (see Ekanayake et al., 2020) by producing only what is needed when needed and allow repetitive use of resources. Other studies supported “adaptability” by promoting lead time reduction (e.g., Zhang et al., 2020), which enhances supply chain capability to adapt in response to disruptions (Ekanayake et al. 2020). Moreover, several studies supported “efficiency” component by promoting OSC resources optimisation and waste elimination (Ekanayake et al. 2020). This includes studies promoting rework reduction (El Sakka et al.

2016), productivity increase (Afifi et al. 2020), waste elimination (Ayinla et al., 2022), failure prevention (Heravi et al. 2021), and learning from experience (Antoniou and Marinelli 2020). Finally, “anticipation” component is supported by studies addressing cross-training (Goh and Goh, 2019), which involve fostering workers’ capabilities to detect and mitigate potential inefficiencies that could disrupt future operations (Ekanayake et al. 2020). This study, however, finds that the two resilience components, capacity and financial strength, are not well studied in previous literature. Table 3 summarises the lean-OSC literature that addresses the resilience components.

-- insert Table 3 here --

Discussion

Upon analysing the literature, several lean tools and concepts were identified and linked to the realisation of different Industry 4.0 and 5.0 design principles in OSC. These tools and concepts may be termed as “lean-OSC tools and concepts”. Figure 5 illustrates these tools and concepts and their support to the identified literature themes. The number of connections (stated as a number between parenthesis) reflects the frequency of support to different themes. Several lean-OSC tools and concepts supported multiple literature themes, highlighting their power in meeting the objectives of different design principles. Particularly, *process simulation* and *BIM* were the most supporting lean-OSC tools to meet a wide range of I4.0 & I5.0 design principles. This suggests the need to have a broad vision in applying the tools or concepts to maximise the potential of meeting I4.0 and I5.0. For instance, the application of process simulation can be extended beyond process virtualisation, by considering potential environmental benefits process simulation can bring (e.g., waste elimination).

One interesting observation in this review is on *resilience principle,* which reveals similarities with several I4.0 design principles, including virtualisation, decentralisation, real-time capability, interoperability, and modularity. That is, reviewing lean-OSC literature from the perspective of resilience principle, as per Ekanayake et al (2020) explanation, reveals several commonalities. This suggests resilience as an overarching principle aiming at employing I4.0 principles to design efficient production systems that can weather potential supply chain disruptions. However, gaps can be identified in the literature with no study identified to address the resilience components of "capacity" and "financial strength", which have a common purpose on determining the level of manufacturers' preparedness and power to avoid disruptions (Ekanayake et al. 2020).

For human centricity, several themes have been addressed in previous literature, including health and safety, empowerment of people, and wider social implications. However, comparing these themes with the enabling technologies for I5.0 as defined by the European Commission (see Müller, 2020) reveals several gaps. For health and safety, lean-OSC literature focused on mitigating ergonomic risk – which is mainly related to the physical impacts, whereas attention is not paid to the impacts on mental health. Employing technology to monitor labour mental health is of crucial importance amid ever increasing popularity of construction industrialisation. For empowerment of people, the literature focused on labour-led process improvements (i.e., Kaizen) and cross-training, with a lack of studies on the application of other emerging technologies, such as collaborative robots and exoskeletons. The main notion behind these technologies is to support human roles by integrating human powers with technological capabilities (Müller, 2020).

For wider social implications, there are extant research focused on enhancing employment prospects through introducing a range of less skills demanding roles (e.g., Kurdve et al., 2018). However, studies on technologies facilitating cross-lingual communication, gestures recognition, and intention prediction are lacking. The importance of these technologies lies on their capability to enhance workplace diversity and inclusion, particularly by extending employment opportunities to people of different languages, education, and disabilities (see Müller, 2020).

For environmental sustainability, the focus of lean-OSC research is directed towards waste and emission reduction with limited research on bridging circularity and lean-OSC in the umbrella of Industry 5.0 (e.g., reusing shipping containers in construction). In this regard, there are no lean-OSC empirical studies on *design for disassembly* and *material passport.* The former involves early design decisions on material choices, module design, and joint selection to facilitate materials recovery at the end of life (Bovea et al. 2016), while the latter concerns the quality and quantity of materials used in products to give information about material recovery at the end of life (BAMB 2020). Together, they give the potential opportunities for creating a cradle-to-cradle circular economy.

Moreover, there are limited research examined the application of lean principles in mitigating the environmental impacts in addition to wastage and emissions, e.g. on on-site construction against the off-site alternatives. Several OSC activities in the construction site, such as earthworks and foundations, still largely influenced by traditional construction practices. Such practices are linked significant environmental impacts, such as soil contamination and destruction of habitants (see Malik and Marathe, 2022).

-- insert Figure 5 here --

Conclusions

Identifying the state-of-the-art tools and concepts in the field of lean-OSC and understanding their contribution to meeting the requirements of different I4.0 and I5.0 design principles have seminal implications. First, the review informs OSC practice of the specific capabilities of different lean-OSC tools and concepts in meeting technological, economic, social, and environmental industry requirements. Further, our findings also provide OSC scholars with a better picture on the unexplored themes, tools, and capabilities in fulfilling I4.0 and I5.0 objectives using lean concepts. This study is the first of its kind to evaluate lean-OSC research from the perspective of I4.0 and I5.0 using a mixed method design.

The review also suggests several directions for future research. They are summarised below:

- Limited studies addressing the resilience components of "capacity" and "financial strength," which determine manufacturers' preparedness and power to avoid disruptions.
- Lean-OSC literature focuses on mitigating ergonomic risk but lacks attention on the impacts on mental health.
- Limited studies on the application of emerging technologies, such as collaborative robots and exoskeletons, to support human roles in the construction process.
- Research gaps in technologies facilitating cross-lingual communication, gestures recognition, and intention prediction, which are crucial for enhancing workplace diversity and inclusion.
- Lean-OSC research focuses on waste and emission reduction with limited research bridging circularity and lean-OSC in the umbrella of Industry 5.0 and lack of empirical studies on design for disassembly and material passport.
- Many on-site construction activities, such as earthworks and foundations, are still influenced by traditional construction practices, which contribute to significant environmental impacts.

Appendix. Analysed literature versus relevant I4.0 & I5.0 design principles.

Year	Authors	Title	Interoperability	Virtualisation	Decentralisation	Real-time capability	Service orientation	Modularity	Human-centricity	Envir. Sustainability	Resilience
2009	Court P.F., Pasquire C.L., Gibb G.F., Bower D.	Modular assembly with postponement to improve health, safety, and productivity in construction	✓						✓		✓
2012	Nahmens I., Ikuma L.H.	Effects of lean construction on sustainability of modular homebuilding							✓	✓	✓
2012	Han S.H., Al-Hussein M., Al-Jibouri S., Yu H.	Automated post-simulation visualization of modular building production assembly line		✓		✓	✓	✓			✓
2012	Giriunas K., Sezen H., Dupaix R.B.	Evaluation, modeling, and analysis of shipping container building structures		✓						✓	✓
2013	Martínez S., Jardón A., Víctores J.G., Balaguer C.	Flexible field factory for construction industry						✓		✓	✓
2013	Yu H., Al-Hussein M., Al-Jibouri S., Telyas A.	Lean transformation in a modular building company: A case for implementation		✓			✓	✓		✓	✓
2014	Isaac S., Bock T., Stoliar Y.	A new approach to building design modularization	✓		✓			✓			✓
2014	Jansson G., Johnsson H., Engström D.	Platform use in systems building			✓		✓	✓			✓
2015	Alazzaz F., Whyte A.	Linking employee empowerment with productivity in off-site construction							✓		✓
2015	Arashpour M., Wakefield R., Blismas N., Maqsood T.	Autonomous production tracking for augmenting output in off-site construction		✓		✓		✓			✓
2015	O'Connor J.T., O'Brien W.J., Choi J.O.	Standardization strategy for modular industrial plants						✓			✓
2016	El Sakka F., Eid K., Narciss T., Hamzeh F.	Integrating lean into modular construction: A detailed case study of company X		✓			✓	✓	✓	✓	✓
2016	Arashpour M., Wakefield R., Abbasi B., Lee E.W.M., Minas J.	Off-site construction optimization: Sequencing multiple job classes with time constraints			✓				✓		✓
2016	Zhang Y., Fan G., Lei Z., Han S., Raimondi C., Al-Hussein M., Bouferguene A.	Lean-based diagnosis and improvement for offsite construction factory manufacturing facilities					✓		✓		
2016	Peñaloza G.A., Viana D.D., Bataglin F.S., Formoso C.T., Bulhões I.R.	Guidelines for integrated production control in engineer-to-order prefabricated concrete building systems: Preliminary results	✓	✓	✓	✓					✓

2017	Viana D.D., Tommelein I.D., Formoso C.T.	Using modularity to reduce complexity of industrialized building systems for mass customization					✓	✓			✓
2017	Heravi G., Firoozi M.	Production process improvement of buildings' prefabricated steel frames using value stream mapping		✓			✓	✓		✓	✓
2017	Arashpour M., Too E., Le T.	Improving productivity, workflow management, and resource utilization in precast construction							✓		✓
2017	Liu Y., Zhang X., Zhu F.	Analysis of Non-Value-Adding Activities in Prefabricated Building Construction Project: Case Study					✓				
2017	Kong L., Li H., Luo H., Lieyun D., Luo X., Skitmore M.	Optimal single-machine batch scheduling for the manufacture, transportation and JIT assembly of precast construction with changeover costs within due dates	✓		✓						✓
2017	Bataglin F.S., Viana D.D., Formoso C.T., Bulhões I.R.	Application of BIM for supporting decision-making related to logistics in prefabricated building systems	✓	✓	✓	✓					✓
2018	Økland A., Johansen A., Olsson N.O.E.	Shortening lead-time from project initiation to delivery: A study of quick school and prison capacity provision						✓			✓
2018	Banks C., Kotecha R., Curtis J., Dee C., Pitt N., Papworth R.	Enhancing high-rise residential construction through design for manufacture and assembly - A UK case study	✓						✓	✓	✓
2018	Kurdve M., Hildenbrand J., Jönsson C.	Design for green lean building module production - Case study		✓				✓	✓	✓	✓
2018	Chauhan K., Peltokorpi A., Seppänen O., Berghede K.	Combining takt planning with prefabrication for industrialized construction	✓			✓	✓				✓
2018	Xu G., Li M., Chen C.-H., Wei Y.	Cloud asset-enabled integrated IoT platform for lean prefabricated construction	✓	✓		✓				✓	✓
2018	Kong L., Li H., Luo H., Ding L., Zhang X.	Sustainable performance of just-in-time (JIT) management in time-dependent batch delivery scheduling of precast construction	✓		✓					✓	✓
2018	Wesz J.G.B., Formoso C.T., Tzortzopoulos P.	Planning and controlling design in engineered-to-order prefabricated building systems			✓						✓
2018	Minunno R., O'Grady T., Morrison G.M., Gruner R.L., Colling M.	Strategies for applying the circular economy to prefabricated buildings								✓	✓
2019	Gbadamosi A.-Q., Mahamadu A.-M., Oyedele L.O., Akinade O.O., Manu P., Mahdjoubi L., Aigbavboa C.	Offsite construction: Developing a BIM-Based optimizer for assembly		✓				✓		✓	✓
2019	Goh M., Goh Y.M.	Lean production theory-based simulation of modular construction processes		✓			✓	✓	✓	✓	✓
2019	Ritter C., Barkokebas R.D., Li X., Al-Hussein M.	Integrated ergonomic and productivity analysis for process improvement of panelised floor manufacturing		✓					✓		✓
2019	Ahmad S., Soetanto R., Goodier C.	Lean approach in precast concrete component production					✓				
2019	Bortolini R., Formoso C.T., Viana D.D.	Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling	✓	✓	✓	✓				✓	✓
2020	Antoniou F., Marinelli M.	Proposal for the Promotion of Standardization of Precast Beams in Highway Concrete Bridges						✓			✓
2020	Yazdi A.J., Fini A.A.F., Forsythe P.	An Integrated Product Planning and Design Platform in the Context of Housebuilding Industry	✓		✓		✓	✓			✓

2020	Thajudeen S., Lennartsson M., Elgh F., Persson P.J.	Parametric modelling of steel connectors in a glulam based post and beam building system - Towards a flexible product platform approach			✓	✓	✓	✓			✓
2020	Li L., Li Z., Li X., Zhang S., Luo X.	A new framework of industrialized construction in China: Towards on-site industrialization						✓	✓	✓	✓
2020	Zhang Y., Lei Z., Han S., Bouferguene A., Al-Hussein M.	Process-Oriented Framework to Improve Modular and Offsite Construction Manufacturing Performance		✓			✓	✓		✓	✓
2020	Afifi M., Fotouh A., Al-Hussein M., Abourizk S.	Integrated lean concepts and continuous/discrete-event simulation to examine productivity improvement in door assembly-line for residential buildings		✓		✓		✓	✓	✓	✓
2020	Bataglin F.S., Viana D.D., Formoso C.T., Bulhões I.R.	Model for planning and controlling the delivery and assembly of engineer-to-order prefabricated building systems: Exploring synergies between lean and BIM	✓	✓	✓	✓					✓
2020	Wang M., Altaf M.S., Al-Hussein M., Ma Y.	Framework for an IoT-based shop floor material management system for panelized homebuilding	✓	✓		✓					✓
2020	Zhang H., Yu L.	Dynamic transportation planning for prefabricated component supply chain	✓		✓					✓	✓
2020	Heravi G., Rostami M., Kebria M.F.	Energy consumption and carbon emissions assessment of integrated production and erection of buildings' pre-fabricated steel frames using lean techniques	✓	✓			✓			✓	✓
2020	Choi J.O., Shrestha B.K., Kwak Y.H., Shane J.S.	Innovative Technologies and Management Approaches for Facility Design Standardization and Modularization of Capital Projects		✓				✓			✓
2021	He R., Li M., Gan V.J.L., Ma J.	BIM-enabled computerized design and digital fabrication of industrialized buildings: A case study	✓	✓		✓		✓		✓	✓
2021	Barkokebas R.D., Ritter C., Al-Hussein M., Li X.	Simulation-based decision support for production improvement using integrated ergonomic and productivity performance indicators		✓				✓	✓	✓	✓
2021	Lerche J., Neve H., Gross A., Wandahl S.	A MODEL TO LINK TAKT SCHEDULES AND OPERATIONS IN CONSTRUCTION	✓			✓	✓				✓
2021	Salama T., Salah A., Moselhi O.	Integrating critical chain project management with last planner system for linear scheduling of modular construction	✓	✓	✓	✓					✓
2021	Heravi G., Kebria M.F., Rostami M.	Integrating the production and the erection processes of pre-fabricated steel frames in building projects using phased lean management	✓	✓			✓			✓	✓
2021	Barkokebas B., Khalife S., Al-Hussein M., Hamzeh F.	A BIM-lean framework for digitalisation of premanufacturing phases in offsite construction	✓			✓	✓		✓	✓	✓
2021	Rosarius A., García De Soto B.	On-site factories to support lean principles and industrialized construction						✓	✓	✓	✓
2021	Ezzeddine A., García de Soto B.	Connecting teams in modular construction projects using game engine technology	✓	✓							✓
2021	Mignacca B., Locatelli G.	Modular Circular Economy in Energy Infrastructure Projects: Enabling Factors and Barriers		✓				✓		✓	✓
2022	Feist S., Sanhudo L., Esteves V., Pires M., Costa A.A.	Semi-Supervised Clustering for Architectural Modularisation	✓		✓			✓			✓
2022	Bao Z., Laovisutthichai V., Tan T., Wang Q., Lu W.	Design for manufacture and assembly (DfMA) enablers for offsite interior design and construction						✓			✓
2022	Ayinla K., Cheung F., Skitmore M.	Process Waste Analysis for Offsite Production Methods for House Construction: A Case Study of Factory Wall Panel Production		✓			✓	✓		✓	✓

2022	Laika M., Heravi G., Rostami M., Ahmadi S.	Improving the Performance of Precast Concrete Production Processes by Simultaneous Implementation of Lean Techniques and Root Cause Analysis		✓			✓	✓		✓	✓
2022	Lerche J., Enevoldsen P., Seppänen O.	Application of Takt and Kanban to Modular Wind Turbine Construction	✓			✓	✓				✓
2022	Du J., Xue Y., Sugumaran V., Hu M., Dong P.	Improved biogeography-based optimization algorithm for lean production scheduling of prefabricated components	✓		✓		✓				✓
2022	Su M, Yang B , and Wang X	Research on Integrated Design of Modular Steel Structure Container Buildings Based on BIM	✓	✓				✓		✓	✓

Data availability statement

All data, models, and code generated or used during the study appear in the submitted article.

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Tables

Table 1. Summary of I4.0 & I5.0 design principles

Design Principle	Definition
Industry 4.0	
Interoperability	the capability of different production equipment, intelligent products, control systems, and stakeholders to interconnect and interact in a value network to enhance information sharing and exchange (Lu 2017).
Virtualisation	the creation of digital twins of physical systems to predict and optimise manufacturing performance (Qi and Tao 2018).
Decentralisation	the quality of smart elements and stakeholders in a value network to autonomously analysis data and take decisions in pursuit of shared organisational objectives (Gilchrist 2016).
Real-time efficiency	the quality of collecting, communicating, analysing, monitoring, and sharing data in real-time to facilitate timely decisions (Hermann et al. 2016).
Service orientation	the strategic focus of production systems on customers' needs and expectations, encouraging timely responses to the market (Kamble et al. 2018).
Modularity	the capability of the production system to flexibly adapt to ever-changing market conditions by adopting more agile supply chain mindset (Ghobakhloo 2018).
Industry 5.0	
Human centricity	the prioritisation of workers' needs and interests in a production system, over technology requirements (Nahavandi 2019).
Environmental Sust.	the pursuit of greener production systems respecting the planetary boundaries by promoting a circular economy mindset (Rada 2018).
Resilience	the capability of the production system to withstand potential supply chain disruptions, especially during the times of emergencies and crises (Breque et al. 2021).

Table 2. Keywords and interchangeable/related terms used in the search.

Keyword	Synonymous/ Related Terms
Off-site construction	"Off-site construction" OR "Off site construction" OR "Offsite construction" OR "Offsite manufacturing" OR "Offsite manufacture" OR "Off-site manufacturing" OR "Off-site manufacture" OR "Off site manufacturing" OR "Off site manufacture" OR "Prefabricated construction" OR "Pre-fabricated construction" OR "Prefabricated building" OR "Pre-fabricated building" OR "Precast Construction" OR "Pre-cast Construction" OR "Industrialized building" OR "industrialised construction" OR "Industrialized construction" OR "modular construction" OR "modular building"
Lean	AND lean OR "value stream mapping" OR just-in-time OR "just in time" OR kaizen OR "process improvement" OR pull-system OR "pull system" OR Kanban OR 5S OR 5why OR "continuous flow" OR "Visual Management" OR standardisation OR standardization OR "takt time" OR "Single-Minute Exchange of Die" OR "Single Minute Exchange of Die" OR "Total Productive Maintenance" OR "Production Leveling" OR "Production Levelling" OR Heijunka OR Poka-Yoke OR Jidoka OR Autonomation

Table 3. Addressed resilience components/traits in lean-OSC literature.

Resilience components	Resilience traits	lean-OSC tools/concepts	lean-OSC Literature
Resourcefulness	personal security	Health & safety tools	(Ritter et al. 2019)
Resourcefulness	collaborative information exchange & decision making	BIM	(Bataglin et al. 2020)
Resourcefulness	collaborative forecasting	BIM	(Xu et al. 2018)
Flexibility	production postponement	JIT	(Zhang and Yu 2020)
Flexibility	modular product design	Design modularisation	(Feist et al. 2022)
Flexibility	multiple uses	standardisation	(Antoniou and Marinelli, 2020)
Adaptability	lead time reduction	Process simulation	(Zhang et al. 2020)
Efficiency	failure prevention	TPM	(Heravi et al. 2021)
Efficiency	rework avoidance	Process simulation	(El Sakka et al., 2016)
Efficiency	labour productivity	Process simulation	(Afifi et al. 2020)
Efficiency	waste elimination	Process simulation	(Ayinla et al., 2022)
Efficiency	learning from experience	standardisation	(Antoniou and Marinelli 2020)
Visibility	efficient IT system & information exchange	BIM	(Bortolini et al. 2019)
Visibility	products, assets, people visibility	LCA, health & safety tools, process simulation	(Kurdve et al. 2018)
Anticipation	deploying tracking and tracing tools	module tracking technology, takt planning	(Wang et al. 2020a)
Anticipation	monitoring early warning signals	Process simulation	(Afifi et al. 2020)
Anticipation	cross training	cross-training	(Goh and Goh 2019)
Dispersion	distributed decision making	LPS, optimisation models, mass-customisation platforms	(Isaac et al. 2014), (Wesz et al. 2018), (Yazdi et al. 2020)

Figure Captions

Fig. 1. The number publications on lean-OSC literature since 2007

Fig. 2. Research design

Fig. 3. Major lean-OSC research network

Fig. 4. Minor lean-OSC research networks

Fig. 5. lean-OSC literature themes in the lens of I4.0 & I5.0 design principle versus supporting tools/concepts (Note: digits between parentheses represent the number of connections revealed from literature)