

Lean-Offsite-Simulation Nexus for Housing Construction: A State-of-the-art Review of the Existing Knowledge

Purpose

The purpose of this current study is to present an overview of the existing knowledge on the combined application of lean, off-site and simulation (LOS) in housing delivery.

Design/methodology/approach:

A systematic literature review approach was adopted. Based on a comprehensive search using SCOPUS, Web of Science (WoS) and the International Group for Lean Construction (IGLC) databases, 66 relevant journal articles were identified and analysed.

Findings:

The study found that the most significant impact of the combined application lean, off-site and simulation in housing delivery are; the capacity to visualise the production processes as a whole in real-time, exposure and removal of non-value adding activities from the production and faster delivery. However, the combined application of LOS is low compared to a single application of each technique in housing delivery.

Practical Implication:

The results provide relevant stakeholders and actors in the housing sector (private and public housing developers, off-site housing manufacturers and constructors, housing associations, and government housing agencies, among others) with the information needed to improve the outcomes of housing delivery through the application of LOS.

Originality/Value:

This study contributes to the ongoing debate on addressing the global housing shortage by presenting an integrated overview of the existing knowledge on the impact of the nexus of LOS and providing compelling evidence for its usage in housing delivery. It also demonstrates how the combined application of LOS supports the achievement of the flow and value view in the TFV model, which was not previously reported.

1.0 INTRODUCTION

The construction industry assembles constructed spaces to house the people living within a geographical space. However, the poor performance of building construction projects leads to the wastage of economic resources (Wuni and Shen, 2019). The increase in housing prices, poverty, unequal access to education and healthcare costs have been linked to the scarcity and inequality in the housing market (Wen et al., 2018). The use of traditional methods of construction has been blamed for the UK government's inability to achieve its target of delivering 300,000 homes per year (Housing, Communities and Local Government Committee, 2019). Together, these studies show that the provision of affordable housing plays a crucial role in the maintenance of socio-economic balance within the society. Hence, there have been calls to adopt newer construction methods to improve the outcomes of building construction projects.

Research into Modern Methods of Construction (MMC), such as off-site construction, lean construction, simulation, building information modelling, digital twins, virtual reality, augmented reality) has been a topical issue in the field of construction management. The current study focuses on lean, off-site and simulation because studies have shown that the use of lean, off-site and simulation (LOS) approaches improves construction projects' outcomes (Bajjou and Chafi, 2020, AbouRizk et al. 2011). Although there is evidence showing the use of lean, off-site construction and simulation approaches in the construction sector, the usage of these techniques is not yet widespread (Pan et al., 2007; Martinez, 2010). For instance, the history of simulation dates back to 1961 (Bokor et al., 2019), but its use in construction project delivery is still not common. This could be due to the complexity of construction project arising from the challenge of modelling the many activities on a project (AbouRizk et al., 1992). However, there are benefits associated with its implementation. For instance, recent studies have shown that when simulation approach is implemented it support the identification and elimination of wasteful processes thus contributing to time and cost saving (AbouRizk *et al.* 2011; Arashpour et al., 2016; Bamana et al., 2019). Zhang et al., 2018 found that offsite has the potential to reduce construction waste arising during the design and construction phase of a project. Additionally, Koskela, (2000) affirmed that the use of lean approach increase output value through systematic consideration of customer requirements.

From these studies, it is clear that the use of LOS is beneficial to construction projects and society at large. Despite their evident benefits, the limited usage has been attributed to the cost associated with its implementation, lack of knowledge and clients' inflexibility in design change and

resistance to change demand, among others (Razkenari et al., 2020; Mellado and Lou 2020; Abbasi et al. 2020). Due to the importance of housing to society, there is a need to show more empirical evidence that can stimulate an increase in the uptake of lean and off-site construction methods in the construction sector.

As stated previously, several studies have highlighted the benefits of using LOS methods in construction projects (Martinez, 2010). Although some studies (Heravi and Firoozi, 2017) have shown that a link exists between the use of LOS and improved project outcomes, others have demonstrated that off-site methods tend to be more expensive than on-site methods. For instance, Polat et al. (2006) showed that the use of off-site methods for rebar is more costly when compared to the on-site approach. Systematic literature reviews studies that focuses on off-site construction exist (Mostafa et al., 2016; Wuni and Shen, 2019); it also exist for lean construction (Singh, and Kumar, 2020 and for simulation (Abdelmegid et al.2020). However, there has been no review on the nexus among “off-site construction”, “lean construction”, “simulation” and “housing”. The current study addresses this gap in knowledge by addressing the research question: What is the state of knowledge on the combined application of "lean construction", "off-site construction", “simulation” in housing delivery and what is current and future research direction in this area? The aim of this current study is to present an overview of the existing knowledge on the combined application of lean, off-site and simulation (LOS) in housing delivery. An overview of the existing knowledge of LOS methods in housing delivery would provide compelling evidence justifying its usage.

The specific research objectives are:

1. To identify the geographical distribution of LOS research related to housing delivery
2. To identify the type of housing projects where LOS approaches was used.
3. To determine the extent of use of the three approaches in a housing project.
4. To identify the factors that support the implementation of LOS in housing delivery
5. To demonstrate the impact of the combined application of LOS in housing delivery through the Transformation Flow Value view Model and to finally,
6. Identify the current research gap on the application of LOS and provide future direction

The study contributes to knowledge by highlighting the trends and gaps in the current knowledge on the subject matter. This information can be used to provide justification for future studies.

2.0 LITERATURE REVIEW

Exploring the Lean, off-site, Simulation nexus in Housing Delivery

2.1.1 Global perspective on housing

Housing is not only a basic need but also a fundamental human right. However, it has been reported that close to 20% of the world's population lack access to adequate housing (UN Habitat, 2017). For instance, the housing deficit in the USA, Australia and South Africa are 2.5 million, 250,000 and 2.1 million homes, respectively. Similarly, the UK government target of delivering 300,000 houses per year was not met for over five years counting (Communities and Local Government Committee, 2019). All of this evidence shows that housing shortage is a global problem. However, commentators have challenged the construction industry that the traditional approach to housing delivery will not deliver the quantity and quality of homes required (Farmer, 2016; Communities and Local Government Committee, 2019). The UK House of Common Committee on housing recommends adopting modern methods of construction (MMC) to improve housing delivery outcomes (Communities and Local Government Committee, 2019).

2.1.2 Offsite Construction

Offsite construction provides controlled environment for regulating quality, protection against changing weather conditions, reduce project schedules by changing the sequencing of workflow, and decrease waste of materials (Hong *et al.*, 2018). Therefore, it facilitates reducing construction waste, cost, time, dust, noise, labour requirement, air pollution and resource depletion (less usage of water, etc.), and promotes improving health and safety and quality control (Jaillon and Poon, 2008 and Hong *et al.*, 2018). Zhang *et al.* (2018) identified that 80% of the research participants agreed that offsite saves time because it allows on-site and in-factory work to go on simultaneously. Furthermore, there is no need for dismantling the temporary formworks which further contributes to saving time. Offsite construction has been used in delivering housing with significant benefits. For instance, it was reported that the use of off-site construction component eliminated the need for construction scaffolding (Tam *et al.*, 2015). Also, Jailon and Poon (2008) showed that 15%, 16% and 65% reduction in project schedules, labour requirement and construction waste, respectively, are associated with the use of off-site construction components. Even with these benefits the barriers to adopt offsite are well established in the literature (Zhang *et al.*, 2018, Jaillon and Poon, 2008, Lovell and Smith 2010, Zhang and Skitmore, 2012 and Zhang

et al., 2014). For instance, Lovell and Smith (2010) mentioned barriers such as long design time (design freeze), costly than masonry, high initial cost, public attitude, unproven durability of offsite dwelling demand uncertainty and attitude of house building industry. These barriers have to be weighed against evident anticipated benefits in order to justify the use of this approach.

2.1.3 Lean Construction

The theoretical concept of lean in construction was started in 1992 with the work of Koskela in which the researcher applied the production philosophy to construction (Bertelsen and Koskela, 2004). The theoretical concept got famous as Transformation Flow Value (TFV) theory of production and laid ground for lean construction to emerge as a discipline (Aziz and Hafez, 2013). Upon recognising the potential benefits of adopting lean production approach in the construction industry, International Group for Lean Construction (IGLC) coined the term 'lean construction' in 1993. It was described as an approach to design and perform construction activities to minimise waste in time, efforts and materials in order to maximise cost-effective value (Babalola et al., 2019). According to Koskela, (2000), lean construction is the application of lean production philosophy to construction to eliminate waste and improve value for the end-user. Implementation of lean construction approach reduce the share of non-value adding activities (waste); increase output value through systematic consideration of customer requirements; reduce variability; reduce cycle times; simplify by minimizing the number of steps, parts and linkages and increase process transparency, among others. However, the adoption lean construction approach in delivering construction project is still low due different barriers identified by scholars. Mellado and Lou (2020) stated that these barriers are lack of lean awareness amongst workers and management, work pressure and fear of failing in the implementation, high cost of lean training, resistance to change and lack of adequate training, among others. However, studies have shown top management support can help to address such barriers (Daniel, 2017).

2.1.3 Simulation

The history of simulation dates back to 1961 (Bokor *et al.*, 2019), but its implementation in construction is believed to be started in 1963 with the work of Teicholz, in which the researcher adopted a link-node model to study earth hauling systems. Construction simulation is the science of developing a computer-based representation of construction production system in order to experiment with it for understanding underlying behaviours of the actual system (AbouRizk et al.,

2011). According to (Bokor et al., 2019), it is a flexible technique with diverse applications which can be used for building models to represent the overall logic of different activities involved in the construction of a facility and the resources required to accomplish tasks. System dynamics (SD), agent-based modelling (ABM) and discrete-event simulation (DES) are the fundamental techniques used in construction simulation. However, the implementation of these techniques depends on the complexity of the problem and the benefit of its implementation has been reported. For example, AbouRizk, (2010) found the benefits of performing analysis using simulation involve less cost, reduced durations, better quality, better understanding of the process, and more certainty in project delivery. Simulation approach support visualisation of the production system before the actual production which enhance the minimisation of bottleneck during production (Arashpour et al., 2016; Goh and Goh, 2019). However, there is complexity in modelling construction process because of the numbers of activities involved (Abdelmegid et al.2020; AbouRizk et al. 1992). Abdelmegid et al. (2020) found that the limited knowledge of simulation among construction stakeholders and the one-off nature of construction project are among the barriers that contribute to the low adoption of simulation in the construction sector. However, the need to reduce the carbon footprint of the construction sector through digitization will showcase the potential of using simulation to achieve this goal.

The Gap and Rationale for the Study

The review of the concept lean, offsite and simulation shows their potential in improving production process in a project. In practice, the lean approach exposes the non-value-adding activities from the production process (Heravi and Firoozi, 2017; Yuan et al., 2020), while the off-site approach support standardisation of the process with improved quality (Hermes, 2015) and the simulation approach support visualisation of the production system (Arashpour et al., 2016; Goh and Goh, 2019)

All of these show that the three techniques support process improvement. However, there is limited evidence on how the three approaches are applied concurrently to deliver housing projects. On this account, the current study conducted systematic literature to gain insight into how the combined application of lean, off-site and simulation (LOS) are used to support efficient housing delivery.

3.0 RESEARCH METHOD

Systematic literature review (SLR) is a well-established approach used to distil built environment research. For instance, SLR has been applied to construction output modelling (Oshodi et al., 2020), construction craftspeople apprenticeship (Daniel et al., 2020) and off-site construction (Mostafa et al., 2016), among others. Although several methods have been used to review the literature (such as critical review and narrative review), ‘replicability’ and ‘rigour’ are some of the advantages of utilising SLR. In the current study, SLR was used to review the extant knowledge on the intersection among the following concepts: “off-site construction”, “lean construction”, “simulation” and “housing”. Due to the importance of reproducibility of findings, SLR is appropriate for addressing the research question stated in the opening section of this paper.

The stages of the SLR used in this study include: (i) identify relevant keywords, (ii) a search of relevant database, (iii) filter of search results based on the inclusion criteria and (iv) content analysis of the papers that met the inclusion criteria. This information emanating from the fourth stage addressed the research question stated in the introduction section. The process used for the SLR is depicted in Figure I.

Insert Figure I here

3.1 Search Keywords: Identification

Based on the research question, four keywords were initially identified for the database search (i.e. “off-site construction”, “lean construction”, “simulation” and “housing”). Several terms (such as prefabricated building) are used interchangeably with off-site construction in Construction Management literature. An initial scoping search was carried out using the ARCOM (Association of Researchers in Construction Management) database to identify all keywords for a comprehensive database search at stage 2. Previous systematic literature review study, for example, Daniel et al. (2019) has used ARCOM database to generate their keywords. ARCOM database was used in the current study because it housed relevant construction management publications.

The search terms deployed for the database search are presented in Table 1.

Insert Table 1 here

3.2 Data Collection

At the second stage, a robust search strategy was adopted to ensure that all relevant studies were identified. In this study, searches were conducted on these databases: (i) SCOPUS, (ii) Web of Science and (iii) IGLC (International Group for Lean Construction). The reasons for the selection these databases are: (i) Hosseini, et al., (2018) and Baykoucheva (2010) showed conducting searches on SCOPUS and Web of Science (WoS) provide an extensive coverage of edited published studies compared to Google scholar (ii) SCOPUS also contain more construction management research when compare to other databases (Hosseini, et al., 2018) and (iii) IGLC provides a platform for showcasing ‘best’ of lean practice in construction projects. The authors did not use Google Scholar because it has been observed that its content changes over time in addition to the nature of its algorithms and structure make it a lesser option for systematic review (Giustini and Boulos, 2013). To ensure that the findings of the study are replicable, it was decided that these three databases are sufficient for conducting the search for relevant materials. The keyword combinations used for the database search are presented in Table 1. The search results are summarised and presented in Table 1. At the end of the search, 141 published studies were identified from the SCOPUS and WoS.

The keyword search approach used in the IGLC database was slightly different from the approach used for the WoS and SCOPUS. This is because the developed search string used in the WOS and SCOPUS return no result from the IGLC database. To overcome this, the keyword search was done for each year from 1997 - 2020. Though tasking, it ensures no relevant publication was missed. The keywords used are “off-site”, “offsite”, “prefabrication”, “simulation” “modular” and housing. From the search 150 relevant articles were identified from IGLC conference proceedings. The search was limited to 2020 because IGLC2021 conference proceedings is not yet available. However, the Scopus and web of science search was limited to 1997- 2021. The year range was selected because there seems to be a rise in lean construction and off-site publication in the nineteen nineties (Google Ngram search, 2021; Google Ngram search, 2021a).

3.3 Filtering of Search Results

The initial search results, i.e. sample, were filtered using the inclusion and exclusion criteria. The implementation of the filtration process ensured that irrelevant studies were excluded from the sample. The filtering process was executed in two stages. First, the title and abstract of each paper (i.e. 291 [141 Journal articles + 150 IGLC conference proceedings papers] papers from the search)

was read. Out of the 291 articles identified from the search stage, 205 [112 Journal articles + 93 IGLC articles] were excluded from the sample. The reasons for exclusion are: (i) overlap of results that emerged from the SCOPUS and WoS search. 84 [84 Journal articles + 0 IGLC articles] duplicates were removed from the collected data; and (ii) Aim of the identified studies. The application of lean, off-site and simulation to housing projects is the focus of the current review. Hence, studies focused on the application of these techniques to other projects were excluded. For instance, Zhou et al. (2020) focused on the application of lean to the production of ship-pipe part and it was removed from the search results. Hence, 121 [28 Journal articles + 93 IGLC conference proceedings articles] articles were excluded due to the focus of those studies. At the end of the first stage of filtering, the search results comprised of 86 [29 Journal articles + 57 IGLC conference proceedings articles] articles.

Second, the full text of the 86 articles was read to ensure that the inclusion criteria, i.e. the focus of the study, was met. 19 [5 Journal articles + 14 IGLC conference proceedings articles] that did not meet the inclusion criteria were excluded from the sample. At the end of the filtering process, 66 [25 Journal articles + 41 IGLC conference proceedings articles] articles remained in the search results.

3.4 Qualitative Content Analysis of Search Results

The 66 relevant article was subject to rigorous qualitative content analysis. The qualitative content data analysis was done in relation to the pre-identified research objectives stated in the introduction. The papers that meet the selection criteria were coded as 01 to 66 for the qualitative content analysis. In doing the content analysis, the coded papers were read to address the research objectives as follows: (i) **country where study was conducted** (ii) housing types; (iii) distribution of the combined application of lean, off-site and simulation (iv) factors that support the implementation; and (v) the impact of the combined application of LOS in housing delivery. Some of the qualitative content result were quantified for better visualization. The outcomes of the study are summarized and presented in Tables 1-3 and Figures 1-5. The result emerging from the review of the extant literature are shown in the subsequent sections.

4.0 RESULTS

This section presents the results that emerged from the analysis of the 66 relevant articles described in the method section. The result and the discussion show the current lean-offsite-simulation nexus with housing delivery.

4.1 Distribution of Lean, off-site and simulation research across countries

The first objective is to understand the geographical distribution of lean, off-site and simulation (LOS) research related to housing delivery. According to Bilotta et al. (2014), academic publications [such as journal papers, conference papers, etc.] could generate evidence that can be used to inform improvement in policy, practice and processes. It can be argued that the research output from a country indicates the level of commitment to the subject matter. For example, the UK government has demonstrated its commitment to reducing carbon emissions by researching to address this problem in recent years (UKRI, 2021).

Figure II shows the geographical distribution of the studies that met the inclusion criteria. Figure II shows that the highest number of studies on the application of lean, off-site and simulation to housing delivery was conducted in the USA, UK, Sweden, and Canada. What stands out in the figure is that 16 of these studies were carried out in the USA. These findings are consistent with those reported in Oesterreich and Teuteberg (2016), which showed that USA, UK, China and Canada are a leader in using modern and innovative methods termed industry 4.0 in the construction industry. However, China is not among the top countries in term of the number of research outputs in the application of LOS in housing delivery. This could be due to the specific focus of the current study on LOS only and with particular focus on their use in housing delivery. Additionally, the emergence of Sweden is not surprising because a recent industry report showed that at least 45% of building construction projects in the country utilises off-site methods (Marshal, 2019).

Insert Figure II here

Further analysis of the result reveals that over 70% of the study reported across these countries are practical implementation. This finding suggests that these countries are true leaders in the implementation of these approaches in housing projects. However, Figure II also shows that no study was published on the use of LOS in the delivery of housing project from the African continent. The non-existence of study that explores the use of LOS approaches in the African

context could be due to lack of awareness of the benefit associated with the combined application of the techniques to housing delivery. According to Rahimian et al. (2017), greater awareness and training is required to support the adoption of innovative techniques such as offsite in African countries.

4.2 Type of Housing Lean, Offsite and Simulation Approaches are Implemented

The second research objective was to identify the type of housing projects where LOS approaches was used. This evidence is essential because the industry is reluctant to adopt new methods due to limited evidence of its benefits and use. Figure III reveals that LOS approaches were implemented in all types of housing developments. It ranges from residential housing construction, industrial building, correctional centres, and commercial development, including multi-storey houses. This evidence refutes the general perception that the use of off-site is only limited to low rise residential houses.

Insert Figure III here

The study found that the LOS approaches were used to construct houses with different floors. For example, 22 prefabricated concrete element floors (Chen *et al.*, 2020), 6 floors made from cross-laminated timber (Bamana *et al.*, 2019) and 8 floors made from prefabricated concrete element (Heravi and Firoozi, 2017). However, the study reveals that the material used influences the maximum height of the buildings. For instance, while prefabricated concrete elements could support many floors, there is a restriction in the number of floors constructed using timber elements. According to Bildsten (2011), limitation in height is a challenge with some of the available off-site solutions.

4.3 Distribution of the combined application of Lean, Off-site and Simulation

The third research objective is to identify the extent of usage of the three approaches in a housing project. Figure IV shows that out of the 66 studies reviewed, only 27.3% (18 studies) used the three integrated approaches to deliver housing projects. The limited use of the combined approach could be due to the cost of deploying them on a project. The study found that there is significant cost in deploying these approaches on a project (Bildsten, 201).

But, the 66 studies use at least one method. Again this shows that using LOS as an integrated approach in the delivery of housing project is not the most typical practice; instead, using one or

two seems to be the regular practice. More need to be done to encourage the integrated use of LOS because of the benefit it offers, as observed in the current study. Notwithstanding, the current number of the combined application of LOS in the housing project seems to show that people now realise the benefits of their integrated applications.

The study reveals that the projects where the integrated approach was applied shows enhanced impact. For example, the simulation element support visualisation of the production system (Arashpour *et al.*, 2016; Goh and Goh, 2019), while the lean approach exposes the non-value-adding activities from the production process (Heravi and Firoozi, 2017; Yuan *et al.*, 2020) and the off-site approach support standardisation of the process with improved quality (Hermes, 2015). The cumulative benefit of the integrated application of LOS was evidenced in the apparent time saving and increased quality, and better client satisfaction (Abbasian-Hosseini *et al.*, 2014; Hermes, 2015). The identified benefits cannot occur when only one or two of the approaches are employed. The LOS approach was used on different types of projects and context. For example, in Canada, Moghadam and Al-Hussein, (2013) apply LOS on a residential building project. On this project, discrete event simulation (simulation), visual management (lean approach) and modular unit (offsite approach) were adopted.

However, the study found that the integrated application of LOS is common with larger companies. So it is worth mentioning that SMEs may struggle to deploy the approach due to the capital outlay and the skill required to implement these methods. According to Bildsten (2011), the initial cost of deployment is among the factors inhibiting its adoption. Therefore, the larger organisation should develop strategies to support the smaller SMEs who may become part of the supply chain with the needed training to acquire the right skill and infrastructure to implement the approach.

Insert Figure IV here

4.7 Factors that Supports the Implementation Lean, Off-site and Simulation in Housing Project

The fourth research objective focuses on identifying the factors that support the implementation of LOS in housing delivery. Through content analysis of the 66 articles, twenty factors support the implementation of LOS to deliver housing project, as shown in Table 2. The twenty factors are

categorised into five core themes: *supply chain management*, *collaborative approach factors*, *organisational management factors*, *technological factors*, and *process factors*. The section below discusses the grouping of the factors.

Insert Table 2 here

Supply Chain Management

The study found that supply chain management plays a significant role in implementing LOS approaches in housing projects. For instance, previous studies (Stehn and Höök, 2004) observed that early involvement of the supply chain supports effective contribution. It provides an opportunity to use the available skills and expertise to identify the appropriate approach to be adopted from design to installation. However, it is not only early involvement of the supply chain that matters; a clear and transparent communication approach also needs to be in place. According to Pasquire and Connolly (2003), a collaborative relationship must be developed with the component suppliers and subcontractors doing the installation on-site. In practice, this entails linking the factory production activities with the on-site production or installation activities (Björnfot and Stehn, 2004). However, some studies (Bataglin *et al.*, 2020) have highlighted the difficulty in managing the interphase between work and specialists, especially with multi-layer subcontracting.

Similarly, Mawdesley and Long (2002) observed that communication between the service contractor and the main contractors could affect the implementation. Supply chain management in off-site construction is crucial because of the various interphases and specialists involved in the delivery process. Thus, early involvement is vital because of the value added to the process and final product. The implication for the off-site construction sector is that a new supply chain management model that reflects the complexity and intricacy of the off-site construction project should be developed. This is because the traditional supply chain management model may not be effective for construction projects that utilise offsite components.

Collaborative approach factors

The study identifies collaborative practice that supports the implementation of LOS. For instance, Mawdesley and Long (2002) found that collaborative contracts, such as integrated project delivery,

design and build, lean project delivery, and a framework agreement with the supply chain, support LOS application on the project. However, traditional contracts, such as the design bid and build approach, could limit the collaboration required to deliver an off-site project (Mawdesley and Long, 2002). The focus of the collaborative agreement is to ensure that the overall project aim is delivered and develop a long-term relationship with the various suppliers. This is important due to the bespoke nature of the delivery of off-site construction project with many suppliers. For example, a modular off-site contractor would want to keep a long term relationship with their component supplier manufacturer.

Additionally, the manufacturers would also like to keep a long term relationship with the suppliers involved in producing any element used in creating the modular structure. The presence of various supply chain in the off-site project supports the transfer of risk down from the production chain to the subcontractors. However, it could reduce the incentives (Bataglin *et al.*, 2020). Additionally, Bildsten (2011) argued that the numbers of suppliers in the process could lead to supplier dominance. To effectively manage the several suppliers involved in the off-site process, genuine collaboration and commitment from the stakeholders is essential. This collaboration can be developed through the use of collaborative contractive contracts, such as framework agreement and Integrated Project Delivery, that support long term relationship building.

Organisational Management Factors

The study reveals that the management's actions at the organisational level support the application of LOS to deliver housing project. Specifically, the study found that top management support, provision of training to the team (Goh and Goh, 2019), promotion of change within the organisation and incentivisation (Tsao *et al.*, 2000) support the deployment of LOS on most of the project studied. Management support is essential in the implementation of any new process and approach. Wuni and Shen (2019) identified top management support as critical factors that support off-site housing construction. This could mean providing the required training and the information technology architecture that support the implementation at the project level.

However, the study found that much attention seems to focus on the factory production process in training with limited commitment to training the on-site process (Yuan *et al.*, 2020). This could be due to the narrow view that off-site construction is all about producing modules and panels in the control environment at the factory. Inadequate training for the site team could lead to the finished

product's quality being compromised on site. Mawdesley and Long (2002) observed that a lack of training of on-site workers involved in the installation of prefabricated modules leads to various problems. While most off-site construction occurs in the factory, it is also crucial to ensure adequate consideration is given to the on-site activities. Otherwise, the gain made from the factory production process could be jeopardised at the end of installation on site.

Technological Supporting Factors

The study reveals that technology plays a central role in applying LOS to deliver housing project. This includes simulation to understudy the production system and 3D to visualise the production process (Goh and Goh, 2019). The study found that using technology supports efficient and accurate information sharing with the various stakeholders in delivering the project (Goh and Goh, 2019). This result aligns with the previous study. For example, in Wuni and Shen (2020), information sharing was among the topmost factors identified. It includes sharing information between the factory team and site team using the various platform. For instance, discrete-event simulation supports sharing information on non-value adding activities in a particular operation. At the same time, it also reveals the benefit of deploying lean techniques on the production system before the actual implementation. This information enables the stakeholder to make a more efficient decision. However, the management must be ready and willing to invest in these platforms.

Process Support Factors

The standardisation of the process and product support the implementation of LOS on the project. It is among the most cited approaches supporting the application of LOS on the project (Yuan *et al.*, 2020). For example, there is standardisation in developing modules, panels, components, and the techniques used in installing the product on site. The production activities in the factory and on-site are well structured. It is worth mentioning that process, and product standardisation is the core advantage of off-site construction approaches over traditional house production. According to Wuni and Shen (2020), standardisation supports a reduction in production cost because of the economics of scale achieved through mass production using similar material, equipment and method. Hermes (2015) found that process standardisation led to improved quality of the finished product. Taking all these together, process and product standardisation are among the core support

factors in implementing LOS to deliver housing projects. Thus, stakeholders should pay adequate attention to it in LOS implementation.

4.8 Impact of the Application Lean, Offsite and Simulation in Housing Delivery

The fifth research objective focuses on identifying the impact of LOS approaches in housing delivery. Although previous studies have shown the effects of off-site, lean as a stand-alone approach in housing delivery, there is limited evidence on the combined use of off-site, lean and simulation in housing delivery. Table 3 presents the impact of the combined use of LOS in housing delivery as reported in the 66 articles. The effects identified were explored and categorised using the Transformation Flow and Value view model (Koskela, 2000).

Insert Table 3 here

Understanding the Impact of the Combined Application of Lean, Off-site and Simulation through the Transformation Flow Value View Model

Koskela proposed the Transformation, Flow and Value model, commonly known as (TFV model), to understand production system behaviour in construction projects (Koskela, 2000). Transformation (T) in the TFV model focuses on converting input into output, which is the traditional approach to construction project management (Daniel and Pasquire, 2019; Sacks *et al.*, 2017).

The *Flow view* (F) and *Value view* (V) propositions in the TFV model was used to understand the combined impact of LOS. The flow view in the TFV model connotes adequate consideration and maintenance of a stable process flow throughout the production process. This process includes information, task, resources, space, people, material and external conditions (Koskela, 2000). This study has found that the combined application of LOS support effective management of the process flow interphases and transparency, which led to the generation of value for the stakeholders. This shows that the flow view linked to the value view. Accordingly, the set of impacts identified in this study that relate to flow and transparency are categorised as *flow and process transparency* impact.

The (V) in the TFV model focuses on value generated from the customer's perspective or the stakeholder. According to Daniel and Pasquire (2019), the customer is not limited to the paying client; instead, it refers to all the stakeholders interested in the final product. The value generation

view entails engaging with relevant stakeholders to arrive at a collaborative solution that meets the yearning of all stakeholders. This was achieved through the combined application of LOS as stakeholders can visualise solutions before actual implementation, and the wasteful process could also be eliminated or minimised. The study found that the flow and process transparency achieved due to the combined application of LOS led to the reduction of wasteful processes, thus generating higher value for all the stakeholders in terms of cost, time, and quality. Again, these sets of impacts identified from this study are categorised as *value view* generation impact.

4.10 Categorisation of the impact of the combined application of LOS using TFV Model

As shown in Figure V, the flow view in the TFV model is linked with the value view. To put it straight, the achievement of process flows will support the delivery of the value view objectives. The flow and process transparency and the value generation impact are discussed below.

Insert Figure V here

Flow and Process Transparency Impact

The study found that the most significant impact of the combined application of LOS in housing delivery is the capacity to visualise the production processes as a whole ahead of time or in real-time. This was reported in over 15 of the publications. The study found that the combined application of LOS supports the clear visualisation of the customer value stream and the entire production system (Gehbauer *et al.*, 2007). The visualisation of the production system was enabled through the combined application of LOS. For example, applying lean techniques supports identifying the value stream in the production process. The use of simulation allows a comprehensive understanding of the processes by visualising the dynamics in the production system (Gehbauer *et al.*, 2007; Heravi and Firoozi, 2017). However, this will not be achieved if only one approach is used. The use of the combined approach supports efficient information-sharing and supports process transparency, according to Bamana *et al.* (2019). Also, the combined application of LOS supports operational process transparency, collaboration and workflow reliability.

The internal production process transparency was enhanced through the combined application of LOS. Larsson (2008) found that the combined application of LOS positioned the project team to reproduce the workflow's dynamic behaviour and analyse different systems to understand their

impact. The importance of this is that the effects of the other variables on the construction process become transparent, supporting improved planning and execution of the task (Arashpour *et al.*, 2016). According to Hermes (2015), it promotes standardisation of the production process, improving the quality of the final product. Studies (Abbasian-Hosseini *et al.*, 2014) have identified another impact of the combined application of LOS, such as the ability to observe on-site project status off-site and visualisation of improvement.

Value Generation Impact

According to Koskela (2000), the principal target of the value generation view is to meet the customer requirement. The study found that the flow and process transparency achieved due to the combined application of LOS contribute to the realisation of the value generation on the project. The uniqueness of the flow view is in its capacity to expose non-value-adding activities in the process (Sacks *et al.*, 2017). The investigation reveals that value generation impact mostly reported is the exposure of non-value adding activities and removal of wastes from the production process. This was reported in over ten publications reviewed. The non-value adding activities are exposed through simulation, first-run studies, value stream mapping, and a just-in-time approach (Gehbauer *et al.*, 2007; Goh and Goh, 2019).

The simulation approach provides a platform for the stakeholders to understand the uncertainty in the production process. Shiau and Wang (202) assert that delay in workflow in construction leads to waste and poor performance. The use of LOS on the project ensures that the interrelationships or interphase between the different flows are adequately understood and managed to minimise uncertainties. However, Pasquire (2012) observes that all the critical stakeholders involved must develop a shared understanding of the task for construction activities to achieve a smooth workflow. The study found that the combined use of LOS in delivering these projects supports developing a shared understanding of the tasks involved in the production process. Additional value generation impacts (time savings, cost savings, fewer accidents, increased quality and less environmental impact) observed as shown in Table 3 can be attributed to the combined application of LOS.

5.0 RESEARCH GAP AND FUTURE RESEARCH DIRECTION

The literature review covers the period between 1997 and 2020. The method depicted in Figure 1 was used to provide answers to the research question, which was described in the opening section of this paper. The review was able to summarise the extant literature into an easy to understand whole and showcase the trends in knowledge. Based on the content of the selected papers, the gaps that can be explored in future research are presented in this section.

5.1 Stage of research

An empirical investigation into a problem generates knowledge for improving practice. The process of knowledge creation through research has been classified into four distinct phases: (i) “description”; (ii) “explanation”; (iii) “prediction” and (iv) “control” (Runeson, 2011; Grove et al., 2015). Based on the review, it is evident that the studies focused on the use of off-site construction methods in housing is at the at the prediction stage, i.e. estimate the likelihood of achieving a specific outcome based on a hypothetical scenario. For instance, Bamana et al. (2019) used a simulation model to predict the influence of productivity using just-in-time (JIT), lean, labour and prefabrication as input variables. Also, Yuan et al. (2020) developed a model for predicting production time for precast components, i.e. wallboards and slabs. These prediction models' knowledge has helped identify sources of waste and processes that require improvements.

Various modelling techniques, especially DES, have been used to: (i) capture the process of producing and assembling precast components; and (ii) predict the outcome of processes. Also, some of these studies have shown that the use of lean principles and prefabrication can improve the outcomes of projects (Bamana et al., 2019; Heravi and Firoozi, 2017). This information from the prediction models feeds into research focused on control, i.e., manipulating the situation to achieve the desired outcomes. Although some of the studies have tested the effects of using lean or prefabrication as an intervention (Afifi et al., 2020; Heravi et al., 2019), most of these studies have been carried out using models or in laboratory conditions. These conditions make it difficult to evaluate the efficacy of proposed solutions in the real world. There is a need for more studies focused on assessing the impact of prefabrication and lean on the outcomes of housing projects. These studies may adopt the use of quasi-experiments or other alternative research methods. The outcome of the proposed studies will enable stakeholders to manipulate housing projects to achieve outcomes desired for practice.

5.2 Research method

The review of the selected papers showed that discrete event simulation is the predominant tool used for modelling the subject matter. Also, it was observed that there is an overdependence on the use of cross-sectional methods for the collection of data. Cross-sectional data makes it challenging to evaluate causality between variables, e.g. the relationship between lean practices and project outcomes. Previous reviews in construction management (AlSehaimi et al., 2013) have suggested the need to adopt alternative research approaches, e.g. action research. Thus, the research methods that can be used in future studies are presented.

First, the use of longitudinal methods for data collection in future studies would provide robust evidence for evaluating the impact of interventions, such as lean practices and prefabrication, on the outcomes of building construction projects. Second, the adoption of unconventional research methods, such as quasi-experiments and action research, would provide real-world evidence for assessing the impact of these interventions on project outcomes. For instance, quasi-experiments could be used to identify the 'best' solutions for a redesign of workspaces used for the production of prefabricated components. Finally, there is a need to identify and implement 'robust' strategies for validating models that are developed in future studies.

5.3 Context

The majority of the studies, which met the inclusion criteria for the review, were carried out in developed countries. These studies have shown the potential benefits of using off-site construction methods in building construction projects. The findings of studies carried out in these two contexts (i.e., developing and developed countries) tend to produce contrasting results. For instance, Bamana et al. (2019) showed that prefabrication and lean could reduce the cost of projects. In contrast, Polat et al. (2006) found that prefabrication increased the cost of projects. Several factors may be responsible for observed differences. First, the non-implementation of lean principles in the study reported in Polat et al. (2006). Second, the absence of infrastructure to ease and lower the cost of transporting prefabricated components in developing countries. Third, instability in the macroeconomic environment, e.g. high inflation rates, low labour costs, etc. Finally, externalities are not considered in those studies. For instance, workers' exposure to inclement weather when working on-site impacts health care costs. There is a need for more studies focused on evaluating the effects of lean and off-site methods on the outcomes of building construction projects in developing countries.

6.0 CONCLUSION

There have been calls to adopt modern construction methods, such as lean, off-site and simulation (LOS), to improve the outcomes of housing delivery. However, an integrated overview of the existing knowledge on LOS, which would provide compelling evidence on the benefits associated with its use, is not available. On this account, the current study conducted a systematic literature review to gain insight into how the combined application of lean, off-site and simulation (LOS) are used to support efficient housing delivery.

The results presented and discussed in the preceding section revealed the trends and gaps in the current knowledge on LOS application in housing delivery. The study found that the *early involvement of the supply chain* and *simulation to visualise the production process* and *standardisation of the process* are the most mentioned factors that support the implementation of LOS in housing delivery. The study reveals that the most significant impact of the combined application lean, off-site and simulation in housing delivery is the capacity to visualise the production processes as a whole in real-time, exposure and removal of non-value adding activities from the production and faster delivery. However, the combined application of LOS is low compared to a single application of each technique in housing delivery.

The study unearths how the TFV model could serve as a framework to gain insight into the impact of the combined application of LOS in housing delivery which has not been previously reported. The study found that the combined application of LOS supports effective management of the process flow activities advocated in the TFV model, leading to reduction of wasteful processes, thus generating higher value for all the stakeholders in terms of cost, time, and time quality. This demonstrates how the *Flow view* contributes to the *Value view* in the TFV model in practice. Regarding the techniques used, the research shows that just in time and LPS, component and panelised system, and discrete event simulation are the most implemented LOS techniques in housing delivery.

The principal scientific significance of the current study to the architecture, engineering and construction sector lies in its contribution to the existing literature on the application of lean, off-site and simulation in housing delivery in the construction industry. It also contributes to the ongoing debate on filling the housing shortage gap by deploying modern and innovative approaches. In this regard, first, the results provide relevant stakeholders and actors in the housing

sector (private and public housing developers, off-site housing manufacturers and constructors, housing associations, and government housing agencies, among others) with the information needed to improve the outcomes of housing delivery through the application LOS to address the housing shortage. Second, the result of the study provides the background information required to justify future research efforts on the application of lean, off-site and simulation to problems in the field of construction management. Finally, the study demonstrates how the combined application of LOS support the achievement of flow and value view in the TFV model.

The current study has its limitations. Firstly, the databases searched was limited to SCOPUS, Web of Science and IGLC. Using different databases could show little difference in the current search results. Secondly, inclusion and exclusion criteria imply that other relevant studies that are not journal articles and are not available IGLC databases were omitted. Thirdly, the articles that were not published in the English language are not included in the study. Finally, the study was limited to the housing or building construction sector. Nevertheless, the method used in the investigation was robust and described expansively to make it replicable. The study recommends that future research explore the research gap identified at the study stage, the method used, and the context of the study.

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