A BIM-lean framework for digitalisation of premanufacturing phases in offsite construction

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Abstract

Purpose – The research introduces means for improving premanufacturing processes (design, procurement and bidding) by leveraging digitalisation in offsite construction. Specifically, this paper proposes a framework that provides measures for the planning and implementation of digitalisation in offsite construction by positioning building information modelling (BIM) as the key technology and lean principles to add value and reduce waste.

Design/methodology/approach – The paper follows the design science research approach to develop the proposed framework and attain the aforementioned objective. The developed framework includes data collection, value-stream mapping and simulation to assess current processes, develop and propose improvements. An empirical implementation is employed to demonstrate the applicability of both the framework and the measures used to evaluate the outcomes.

Findings – The application of the proposed three-stage framework resulted in 9.45%–23.33%-time reduction per year for the various improvement categories in premanufacturing phases. Employing simulation and applying the developed measures provide incentive for upper management to adopt the suggested improvements. Additionally, while the empirical implementation was tested on a modular construction company, the methods used indicate that the framework, with its generic guidelines, could be applied and customized to any offsite company.

Originality/value – While several studies propose that BIM-Lean integration offers an advantage in the context of production systems, this paper focuses on the initial design and planning phases, which are mostly overlooked in the literature. Moreover, the present study provides quantitative evidence of the benefits of data integration through BIM technology.

Keywords Digitalisation, Process digitisation, Offsite construction, BIM-Lean

Paper type Research paper

1. Introduction

Offsite construction is an approach that reduces construction time, defects and risks by manufacturing building components in a factory-like environment and installing them at their final destination onsite (Mostafa *et al.*, 2016). In spite of the recognised benefits, offsite construction still faces several challenges as researchers discuss these issues and suggest ways to overcome them. Bataglin *et al.* (2020) argue that the short lead times required to accommodate clients' requests and the complexity involved in managing different projects being manufactured at the same time as the main challenges in offsite construction projects. By providing an integrated solution (design, procurement, manufacturing, and installation) based on the client's requirements, offsite contractors take on the majority of the risk while dealing with a range of different professionals such as consultants, suppliers, plant managers and construction personnel. Information transmitted by the client that is translated into

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drawings, commercial proposals and design specifications must be consistent and shared throughout the process to avoid waste, such as cost overruns, and product nonconformity (Li *et al.*, 2018a, b). Building information modelling (BIM) has been used to streamline the flow of information while facilitating the use of digital technologies in offsite construction even though its implementation has not received widespread attention (Luo *et al.*, 2020). Indeed, despite evidence of the benefits of using BIM to digitise and enhance design and procurement processes in offsite construction, Razkenari *et al.* (2020) argue that most benefits are not yet measured or quantified.

Seamless data flow and the integration of different information systems is crucial for efficient product development and management (Caldas *et al.*, 2005). In this context, Grieves (2006) pointed out that there is a substantial cost associated with the rework required to deal with information isolated between departments (e.g. sales, engineering, estimation) and the re-creating or reconstructing of missing/ incomplete information in inter-departmental work. Indeed, Agarwal *et al.* (2016) attribute the construction industry's poor productivity to a lack of information sharing happening in a timely manner, which results in stakeholders often working on different versions of documents creating disagreements and additional cost. Thus, Agarwal *et al.* (2016) recommend digitalisation and define it as working in an environment where information is digital, changed in real-time and transparent to ensure better and more reliable outcomes. Moreover, Ghaffarianhoseini *et al.* (2017) claim that continued digitisation will allow the construction industry to reinvent project design and delivery processes and position BIM as a key technology in this initiative. In this context, BIM is used to bridge information gaps in various areas such as schedule and project coordination between stakeholders (Ocheoha and Moselhi, 2018).

Moreover, offsite construction has benefited from concepts derived from other domains, such as lean manufacturing. Through its premise of minimising waste and adding value to the process, lean construction provides tools to identify and minimise wastes in offsite operations (Innella *et al.*, 2019). Indeed, lean philosophy provides a comprehensive framework to propose and quantify improvements in construction-related processes, such as the implementation of BIM or its integration with different information systems.

Despite relevant work in the area, Yin *et al.* (2019) argue that researchers have yet to create criteria and quantify the improvements that result from the adoption of BIM for its wider adoption in offsite construction. Organisations acknowledge the benefits inherent to the integration of BIM with other information systems to harness their advantages, yet further research is required at the organisational level to quantify the benefits from these implementations (Lu and Korman, 2010). Additionally, the adoption of the lean approach in offsite companies shall be guided early on from the design phase, and research needs to examine the help of advanced technology to support lean techniques in achieving its full potential (Innella *et al.*, 2019).

Accordingly, this research proposes a framework to introduce digitalisation in offsite construction premanufacturing phases (pre-bidding, design and procurement) using a BIM-Lean approach where BIM is characterised as the main source of project-related information; while lean philosophy is applied as a guiding principle to identify and minimise wastes in current and future processes. The proposed framework integrates BIM and other information systems to improve inter-departmental communication focusing on three organisational needs: improved planning, improved information exchange and quantification of improvements. The motive behind this research is to provide offsite construction companies a roadmap for improving their performance during premanufacturing phases while also providing methods to quantify improvements due to digitalisation. This study contributes to the body of knowledge by providing a well-defined reproducible approach that serves as a guide to digitalize and improve processes in the offsite sector using BIM, lean principles, and other tools. Additionally, the suggested measures for tracking the improvements will benefit practitioners by having recorded evidence of improvement while establishing a culture of continuous improvement at their organisations.

2. Research background

Gartner (2020) defines digitisation as the process of transforming analogue information to digital without changing the process itself; whereas digitalisation (or process digitisation) is the use of digital technologies to transform processes and produce value-adding opportunities. Therefore, premanufacturing processes in offsite construction are highly digitised given the predominant use of spreadsheets, digital construction drawings and the use of enterprise resource planning systems (ERP) to design, estimate and bid projects. In fact, despite advancements of BIM in offsite construction and growing demands for customisation in the industry, premanufacturing may become a future bottleneck since its processes are still carried out manually and rely heavily on experience (An *et al.*, 2020). Hence, offsite construction lacks digitalisation as it continues to conduct its processes in an analogue manner with digitised tools. While BIM research has been focused on methods and tools at the practical level (Santos *et al.*, 2017), Yin *et al.* (2019) argue that researchers must create criteria and quantify the improvements attributable to BIM in offsite construction to further its adoption. Indeed, BIM is not fully implemented in companies due to traditional management strategies and short-term goals where the lack of guidance and assertive procedures form a major barrier to BIM implementation (Al Hattab and Hamzeh, 2018). To bolster the use of BIM and digitalisation at an organisational level in offsite construction, this research applies lean philosophy given its origins in manufacturing and previous applications in offsite construction.

Many studies offer frameworks and approaches to incorporate lean philosophies into offsite construction, as continuous efforts are made to transform the industry into a highly efficient and cost-effective one (Zhang *et al.*, 2020). Value-stream mapping techniques have been fundamental lean tools used to identify the current state and its areas of improvement, then redesign processes to maximize performance by identifying and quantifying waste (Howell and Ballard, 1998). Three different types of waste are found in activities: value adding, necessary waste (i.e. non-value adding but necessary activities to the process) and pure waste, which are non-value adding activities and can be eliminated from the process (Lee *et al.*, 1999). Discrete event simulation is another tool applied successfully by lean practitioners in offsite construction to forecast different scenarios and establish measures for future state scenarios (Goh and Goh, 2019). Furthermore, simulation has helped in providing means to test the concepts of lean in construction simulation, and templates have been suggested to quantify the impact of implementing such concepts (Farrar *et al.*, 2004). Other studies focus on implementations for process improvement by developing measures to evaluate current and future states of shop floors (Karim and Arif-Uz-Zaman, 2013). Regardless of the tools applied, Innella *et al.* (2019) point out that the full potential of offsite construction will be achieved once lean principles are used with the support of technology to integrate knowledge across different phases of the project. Hence, there is a need for a framework to promote the digitalisation of offsite construction organisations during early stages taking into consideration the differences inherent to each company and the inherent uncertainties involved in applying predetermined measures to measure its impact.

Several studies have investigated the combination of BIM and lean methods to improve processes in the offsite construction sector. For instance, Moghadam (2014) offers an integrated BIM-Lean framework for offsite manufacturing operations mapping the current state and proposing improvements through simulation while generating data and shop drawings for modular projects. Gbadamosi *et al.* (2019) propose a framework to optimise the constructability of prefabricated building components by applying lean principles and optimisation algorithms in BIM models to leverage the design of building envelope components. The literature acknowledges the benefits of both lean principles and technologies, such as BIM, and emphasise the necessity of incorporating these concepts into the curricula (Li *et al.*, 2018a, b). Indeed, Jin *et al.* (2018) identify the integration of BIM and lean with technological applications as a strong research trend in the following years during their review of offsite construction topics.

However, even with the implementation of information technologies (BIM) and lean frameworks into offsite construction processes, factories still encounter major challenges as the whole sector remains behind (Fenner *et al.*, 2018). This is likely the result of a disconnect between current studies and current practices where BIM-Lean approaches are in dire need of being integrated with other digital technologies (Hosseini *et al.*, 2018). Additionally, Al Hattab and Hamzeh (2017) claim that the impacts attributable to the integration of lean practices and BIM in the flow of design-related information and communication between different departments have not yet been realised, nor have measures been proposed to quantify the benefits. As such, more studies are needed to evaluate the combination of BIM, lean, and other tools to improve offsite construction through the digitisation of its processes and to provide empirical case studies of implementation to demonstrate applicability.

In summary, this research identifies the following problems and gaps in the literature: (1) the misuse of digital strategies in premanufacturing phases of offsite construction companies, where BIM and other digital technologies are not fully implemented, (2) the lack of quantitative measures that facilitate the assessment and implementation of these digital strategies and (3) the little attention in the literature given to premanufacturing phases when compared to the fabrication phase. Consequently, the paper herein presents a tested framework to leverage digitalisation in the premanufacturing phases of offsite construction using a BIM-Lean approach, predetermined measures and simulation.

3. Research methodology

This paper implements the design science research (DSR) methodology to propose a framework for improving premanufacturing processes in offsite construction. DSR involves the development of an artefact to resolve a relevant problem identified in a specific environment, for which the effectiveness and contribution should be demonstrated and rigorously explained (Hevner *et al.*, 2004). In this research, the artifact is a BIM-lean framework to improve premanufacturing processes in offsite construction using digitization. Developing the framework follows a six-step process (Peffers *et al.*, 2007), as follows:

(1) Identify the problem under study and the main motivation;

(2) Define specific objectives to address the specified problem;

(3) Design and develop the proposed artefact;

(4) Test and demonstrate the artefact's implementation through established methods in a specified environment;

(5) Evaluate the artefact's effectiveness based on a proposed experiment and

(6) communicate the artefact through publications.

In step one, the major challenges in offsite construction were identified by reviewing the state-of-the-art literature and engaging in discussions with practitioners. Step two focused on identifying the objectives based on the involvement of one of the authors with four different offsite companies and based on the extensive review of common challenges found in these organisations. The objectives of this research were thus determined to be the quantification of improvements from digitalisation and integrating data exchange in the context of the use of BIM in offsite construction companies. In step three, the framework was carefully developed through applying lean philosophy and concepts to account for the possible differences in offsite companies while serving as a generic guideline for proposing and implementing improvements step by step.

Multiple lean principles are adopted in this framework. Mainly, the framework utilizes value-stream mapping to identify current wastes and then forecasts future processes after minimizing wastes. The objective of the mapping exercise is to minimize waste and improve the existing workflow by digitising processes when applicable and by using the measures proposed in this research. Two types of variation are encountered in offsite construction premanufacturing processes: (1) variation caused by internal processes at the organization, and (2) variation caused by the range of project specifications offered to clients. While the first type of variation should be minimized using different approaches ranging from low-tech solutions to the implementation of digital solutions, digitalisation is applied to minimize the effects from the second type of variation. The latter is because external customers value the high range of options offsite construction offers to them.

Indeed, the framework takes into consideration the voice of the customer being the internal customer (different teams within the organisation) or the external customers (offsite construction clients). Forecasting is part of this exercise to promote pull from the customer. Moreover, the framework advocates continuous improvement (i.e. kaizen) of current processes by constantly repeating the framework to identify new improvement opportunities. The overall objective is to have continuous flow of information. Furthermore, it calls for implementing Genchi Genbutsu, a lean principle that is helpful in identifying the peculiarities of a given organisation and requires being physically present to investigate and understand the process. Lean construction calls for releasing work by achieving flow where you can, pull where you cannot, and push where you must.

To this end, the process of developing the framework was iterative. The proposed framework specifies the required input and data from the company while providing details to identify and account for variations in each company, that is the framework highlights the needed practices to develop the context-specific improvements. By applying simulation and statistical tools expressed in the framework, the current state of premanufacturing processes is quantified while the impact of future digitalisation is forecasted at the company under study. At step four, test stage, an empirical implementation was used to: (1) help in establishing the instructions or steps in the framework, and (2) demonstrate the effectiveness of the framework. A detailed explanation of the implementation is provided in Section 5. Step five included the evaluation of the proposed framework by recording the observed results. Lastly, the present study communicates the importance of the problem and the effectiveness of the artefact as part of step six of the DSR. The framework targets different departments working at premanufacturing phases in offsite construction companies to improve their processes by digitising their work while providing quantitative evidence so the upper management can make the required investment for the proposed digitalisation plan. The detailed explanation of the framework is clarified in the next section.

4. Proposed BIM-lean framework

The proposed framework, presented in Figure 1, includes the methods employed to quantify the impact of digitalisation achieved by automating and integrating BIM and other information systems in offsite construction companies. The guiding principles of this framework are presented taking into consideration characteristics identified in each area (offsite construction, lean and digitalisation) at earlier sections. The specific context of offsite

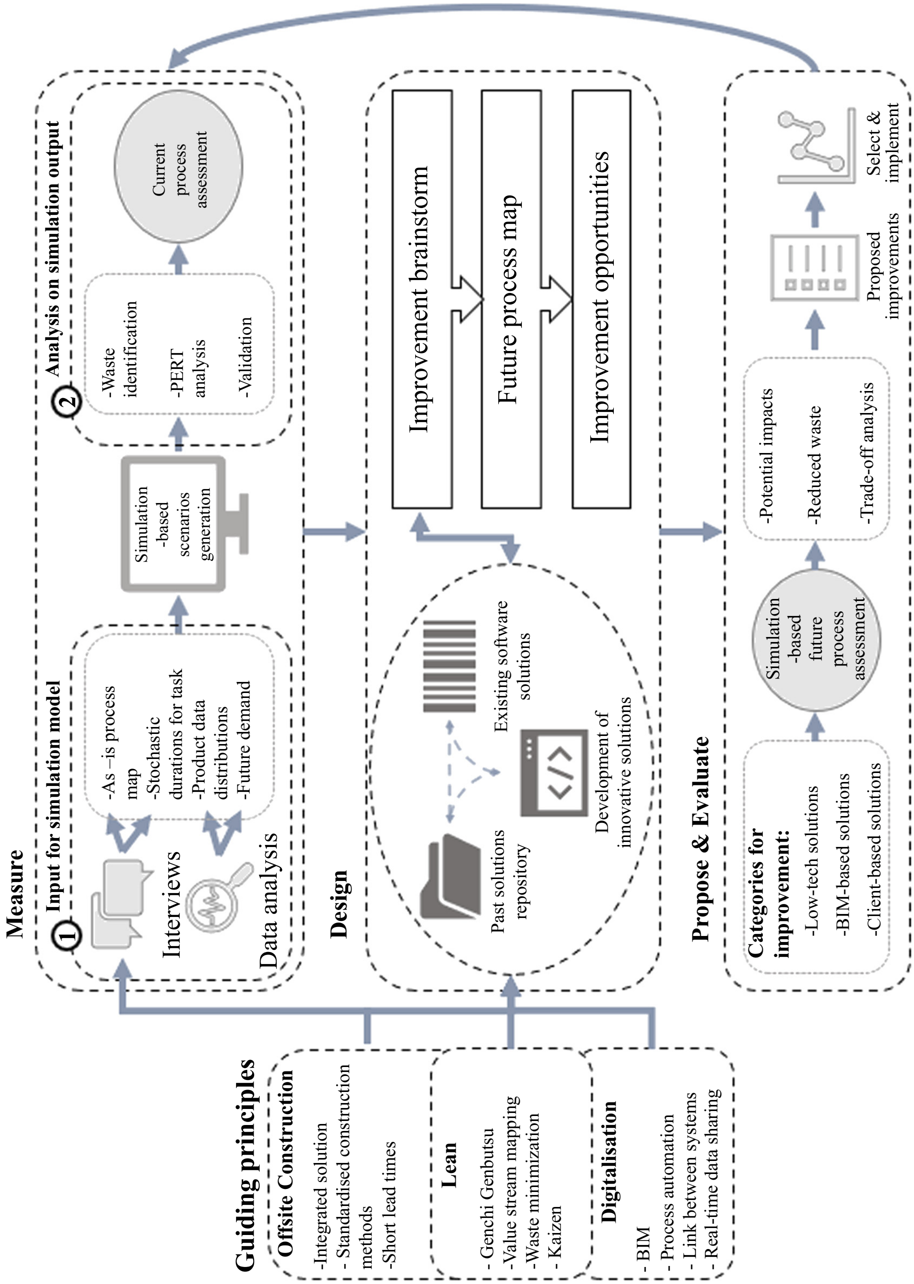

Figure 1.
Proposed framework for digitalisation of premanufacturing phases in offsite construction

construction – where an integrated solution (design, procurement, and construction under the same company) is presented following standardized construction methods under short lead times – is a determining factor for mapping premanufacturing processes. Moreover, lean is applied to align offsite construction practices and digitalisation features through the lean principles mentioned earlier such as conducting *in situ* observation (i.e. *Genchi Genbutsu),* mapping of activities, achieving continuous flow of information and applying continuous improvement (i.e. *Kaizen*) to identify and minimize waste in the process. The digitalisation of design and procurement of building components is proposed by using BIM as a means to generate, store and transform project-related data. By working with BIM-based tools, the digitalisation of premanufacturing tasks is proposed by connecting different systems (e.g. BIM, ERP), automating processes and sharing data between departments in real-time.

Lean philosophy is applied as the guiding principles to measure, identify and implement opportunities for improvements. This framework is therefore divided into three stages as demonstrated in Figure 1: stage (1) is *measure*, which involves measuring the current processes observed at the organisation, stage (2) is *design*, which involves identifying and designing opportunities for improvement based on the previous assessment and stage (3) is *propose and evaluate*, which involves proposing opportunities and forecasting the impact of implementing the identified opportunities at the design stage. In summary, the measure stage maps and quantifies the current situation of the addressed offsite organisation, whereas the remaining stages suggest improvement opportunities (i.e. design stage) while proposing these opportunities based on simulation models that forecasts their impact on the same organisation (i.e. propose and evaluate stage). Simulation is applied at the first and third stages to estimate durations and variations in the process taking the inherent identified uncertainties into account. The proposed framework must be replicated after a testing phase of improvements to allow company experts to measure the impact of the implemented changes and propose new ones, thus creating a culture of continuous improvement around the digitalisation of premanufacturing processes.

Table 1 summarizes which lean and BIM-based principles were applied to the steps of the proposed framework. Lean philosophy is applied at every stage of the framework while the digitalisation of processes acts as an enabler for improvements at the addressed company and is only present at the later stages of the process. Hence, while lean principles such as *genchi genbutsu* and VSM are applied for data collection and analysis, kaizen and waste minimization are applied concurrently with digitalisation principles to plan and improve future processes. During the development and implementation of the proposed framework, it is important to understand how the impact of parametric modelling from BIM differs from processing real-time data from different information systems (e.g. BIM, ERP systems, etc.). While the first enhances the quality and speeds the process of design and drafting, the second

		Measure		Design			Propose and evaluate	
		1	2	3	4	5	6	7
Lean	Genchi Genbutsu	X		X				
	Kaizen			X				X
	VSM	X			X			
	Waste minimisation		X	X		X	X	
BIM-based digitalisation	Parametric modelling			X		X		X
	Real-time data processing			X	X	X		X

Note(s): 1: Input for simulation model; 2: Analysis on simulation output; 3- Improvement brainstorm; 4- Future process map; 5- Improvement opportunities; 6- Opportunities selection; 7- Implementation and re-evaluation

Table 1. Guiding principles applied to proposed framework steps

may change the way and the sequence of present tasks since information between departments is shared continuously (e.g. real-time unit costs for bid proposals and current production status at the shop floor). Hence, BIM-based digitalization principles will play as a decisive factor in how tasks will be performed in the future, while lean principles will help forecast and address its actual impact (i.e. kaizen).

4.1 Stage 1: measure

This stage is divided into two procedures: (1) data collection used as an input for the simulation model, and (2) analysis on simulation output to measure current process performance at the company under study. The measures calculated at this stage are used as a benchmark and indicate the current state of process digitisation at the company taking into consideration both performance and uncertainties forecasted by the simulation model.

4.1.1 Input for the simulation model. Through semi-structured interviews and analysis on historical data provided by the company under study, value-stream mapping for the current state was developed based on lean techniques, and sales forecasts were established. The resulting current-state maps, containing tasks durations estimated by the organisation's experts (e.g. engineers, managers, etc.), and forecasts are used as inputs for the simulation model to estimate different scenarios. At this stage, the organisation must appoint experts who directly oversee or perform the mapped tasks to indicate the current situation as close to reality. The semi-structure interviews are carried until both parties (i.e. the organisation and research team) are satisfied with the level of details mapped, and their duration is dependent upon the length of the mapped tasks. Tasks are grouped into two main phases: (1) pre-award, including all work required to prepare documents to participate in bids; and (2) post-award, including all work performed after the bid event in case the proposal was awarded. Due to the uncertainties inherent in the development of offsite projects, task durations are estimated by experts since they depend on factors such as project size, the complexity of the project, and the inherent uncertainty of the process (e.g. low productivity, changes from client, etc.). For instance, if a task duration is collected and mapped as a range (e.g. 16–24 h) or as discrete values (16, 24, and 30 h), it is modelled as either a uniform or triangular distribution in the simulation model, respectively.

Besides mapping the process, the research team also classifies each task as value-added, necessary waste or pure waste. This classification is based on the nature of the work, that is whether it is directly affecting the end-product, whether it is merely related to the processes needed to manage the work or whether it can be removed or replaced. Likewise, event occurrences such as changes in design, rework and sales forecast are estimated in the form of likelihoods and scenarios. The simulation input combines data from the organisation's historical data (e.g. number and size of projects developed in a year, sales forecast, etc.) with information based on the company experts experience. Together with the current state value stream map, sales forecast is an input to the simulation model to estimate the volume of work the organisation under study will undertake in the future and whether the investment in process digitisation is justified.

4.1.2 Data analysis on simulation output. The developed simulation model reports the maximum, average and minimum durations for each task followed by a sales estimate of how many proposals are rejected (J) and awarded (A) per year. These durations and volume of work are assigned to each phase and presented as pessimistic (P), realistic (R) and optimistic (O) scenarios. This framework applies the program evaluation and review technique (PERT) to calculate the expected duration (E) and coefficient of variation (CV) of pre- and post-award phases under project-related uncertainty (e.g. durations of tasks, project features, etc.) as per Eqns (1) and (2), respectively. Eqn (3) incorporates uncertainty that falls outside the engineering team scope such as the yearly number of rejected and accepted bids provided by the sales forecast. The equation is used to calculate the total number of hours (H) spent by the organisation thus indicating the volume of work expected from the company. Validation from the team of experts is required at this point to address the current situation of premanufacturing tasks and suggest impactful solutions. This can be done using different methods such as Delphi, nominal group, and face validation by a third-party with relevant knowledge of the process. After the analysis is validated, the design stage of the proposed framework is initiated to identify potential solutions based on the measures derived from Eqns (1)–(3).

$$E = \frac{P + 4 \times R + O}{6} \tag{1}$$

$$\mathrm{CV} = \frac{P - O}{6 \times E} \tag{2}$$

$$H = (A + J) \times E_{\mathrm{pre}} + A \times E_{\mathrm{post}} \tag{3}$$

where:

E: Estimated duration from different simulated scenarios

P: Simulated duration for the pessimistic scenario

R: Simulated duration for the realistic scenario

O: Simulated duration for the optimistic scenario

CV: Coefficient of variation

H: Total hours spent on mapped tasks by the team in a year

E_{pre}: Estimated duration per project at pre-award phase

E_{post}: Estimated duration per project at post-award phase

A: Accepted bids in one year

J: Rejected bids in one year

4.2 Stage 2: design

At the design stage, solutions for improvement are identified and developed based on the analysis from the simulation model output and based on whether the tasks are value-added or not. The specific context of design development and procurement in offsite construction is a primary factor at this stage. Given the low number of offsite construction companies and documented case studies in the area, this framework becomes a repository of solutions and improvements for offsite construction premanufacturing phases which is expanded according to the number of companies addressed. Combined with this repository, existing software solutions (e.g. BIM-based software, ERP systems, database management systems, etc.) are tested while the development of further innovative solutions not available for the context of offsite construction are suggested as means to fill a gap identified at the measure stage. An improvement brainstorm is performed by the research team to identify possible improvement suggestions based on the mapped tasks and internal expertise. Besides what was previously mentioned, expertise requires knowledge in different areas such as project management, design development and software development in case some solutions can be developed specifically for the company under study. After the brainstorm session, a list of possible improvements is developed considering potential impact on task durations at the current state. The improvements are classified under one of the following three categories: (1)

low-tech solutions, where changes are proposed by improving processes without the introduction of new technologies; (2) BIM-based solutions, where processes are digitized by commercially available software and (3) client-based solutions, in which digitalisation solutions are designed specifically for the addressed company taking into consideration tasks mapped at the measure stage. By following lean principles, the proposed framework prioritizes low-tech solutions over the remaining categories when its forecasted improvements are not significantly higher according to the simulation models. This decision is made to improve current premanufacturing phases in offsite construction by improving the flow in their processes without having to invest heavily in digitalisation (e.g. software, hardware and training), but rather by focusing on the existing personnel and current practices applied at the addressed company. Indeed, the effort to digitize premanufacturing phases in offsite construction must address the significant wastes at the current processes to be effective and pursued by the organisation.

Future value-stream maps are developed based on each improvement category. These maps address changes in the process regarding the duration of tasks and the impact of adding and/or removing tasks from the mapped workflow. The authors of the present study use future value-stream maps to discuss the proposed changes with the team and identify the validity of these changes in terms of practical implementation at the company under study. After discussing these changes internally and with the organisation, a list of improvement opportunities for the mapped tasks is provided taking into consideration their impact on the total duration and current workflow identified in the previous stage. The work performed during this stage is used to provide input for the future state simulation model to determine the impact of process digitisation for each improvement category.

4.3 Stage 3: propose and evaluate

The propose and evaluate stage presents changes in mapped processes in each improvement category as forecasted by the future state simulation model. By replicating the post-simulation calculations for each improvement category, the potential improvement is presented taking into consideration the organisation's own data and the inherent uncertainties mapped in the process. During the analysis, the quantification of the estimated improvement is approached three ways: (1) average duration per project as per Eqn (1); (2) wasteful tasks in the process (value-added, necessary waste, and pure waste); and (3) coefficient of variation as per Eqn (2). Meanwhile, the average duration per project is often the primary metric employed to measure process improvement. The proposed framework acknowledges the team's current waste and variation as equally important in determining the rate at which the team generates value and how the duration of a project varies.

Moreover, Eqn (3) calculates the total hours saved in a year in each improvement category to provide company experts with the overall impact of the proposed improvements. The results from current and future states are compared and options for process improvement are demonstrated to the organisation according to their quantitative impact. Then, a qualitative assessment of the improvements is undertaken to identify intangible outcomes such as improved communication. Once a complete analysis is performed, the organisation must choose which process improvement suggestions will be selected for implementation and tested for a period. After this period, the proposed framework must be applied once again to determine the impact and identify new opportunities for improvement.

5. Empirical implementation

The empirical implementation of the proposed framework involves one of the largest modular contractors in Brazil specialised in temporary and permanent construction of commercial projects. While the commercial department is decentralised in nine different branches for wider sales coverage across the country, all estimation and engineering work is centralised at the company's main headquarters and factory which are approximately 700 km apart. This geographical limitation requires the company to rely on emails and a commercially available ERP system for all inter-departmental communications while relying on computer-aided design (CAD) systems for design development. Here, all project-related information is manually interpreted in the form of text or schedules from quantity take-offs. This section is divided according to the proposed framework in Figure 1 where the current state at the company is measured, and solutions for improvement are designed, and then proposed.

5.1 Implementation of framework: stage 1 (measure)

5.1.1 Input for simulation model. For two months, nine semi-structured interviews were conducted on weekly basis with experts in each department to identify and determine durations for each task. A total of four experts were interviewed to map all tasks required according to each expert's expertise and practical experience in the addressed phases. Table 2

Phase	Task name	Type	Likelihood	Task duration (hr) *P*	*R*	*O*	Observation
Pre-award	More information from client	PW	30%	16–24	8	1.5–2	
	1st Layout development	VA	100%	5		4	
	3D model development	NW	15%	6–8		2	
	Rendering	VA	15%	6–8		2	
	Commercial to respond client	NW	60%		1		
	Engineering to respond client	NW	12%	1.5		1	
	Project quantity take-off	VA	100%	10–20	20–40	40–60	min per module as project complexity
	Client adaptations on 1st revision	NW	S:65% R:30%	8		0.17–0.33	
	Client adaptations on 2nd revision or more	NW	S:30% R:15%	40% of previous revision			
Post-award	Special items and quantity take-off	NW	100%	8	4	2	as per project complexity
	Special items to ERP	NW	100%		7 min		per special item
	Electrical design	VA	100%		1.3		per module
	Plumbing design	VA	100%		1		per module
	Electrical design rework	PW	7.5%		2.5		
	Plumbing design rework	PW	5%		2		
	Openings and partitions design	VA	S:90% R:10%	2 5	5 10	9 15	1–10 modules 11+ modules
	Revised quantity take-off	NW	100%	10	20	40	as per project complexity
	Registry to ERP system	NW	100%	10–20	20	40	as per project complexity

Note(s): VA: Value-added, NW: Necessary waste, PW: Pure waste, *P*: Pessimistic scenario, *R*: Realistic scenario, *O*: Optimistic scenario

Table 2. Information of tasks collected during interview process

depicts all the mapped tasks identified during the semi-structured interviews and the likelihood of event occurrences, stochastic durations and the task type (value-added, necessary waste or pure waste). A likelihood lower than 100% means the mapped task may not occur depending on requirements from the client or the nature of the project. These tasks, combined with durations dependent upon project features, are the main drivers of process uncertainty that reduce the ability of managers to plan available resources during the year. As previously mentioned, stochastic durations are applied to allow experts a more representative duration of their tasks and to acknowledge the uncertainty of design, bidding, and procurement phases at the company. These durations represent the time experts spent working on each task, but they do not take into account time that is out of their control, such as the duration of the entire bid event conducted by the client or time spent waiting for quotes from suppliers.

As demonstrated in Table 2, the major uncertainties in pre-award tasks depend on the occurrence of events that are most often related to interactions with the client. These include, for instance, providing extra documents, such as renderings, for better clarification of the project. Uncertainty in post-award tasks is driven by a project's features such as its complexity and number of modules to be designed. Project complexity at the company under study is quantified according to the number of special items in the project that are customised items and that have never used by the company before. These items must be outsourced, registered at the organisation's ERP system, then purchased and installed at the factory while complying with an unknown delivery time from suppliers. After collecting all data required during interviews, current-state value stream maps are prepared, and then validated through consensus and face validation by the company's experts and managers.

In addition to the information provided during the semi-structured interviews, other data are collected by analysing historical data from the company in two areas: (1) estimated number of modules per project to indicate project size, and (2) sales forecasts indicating the number of projects the company expects to bid and award during the year. The number of modules per project is acquired by analysing and curve-fitting historical data containing past projects awarded by the company for two years containing a dataset of 235 projects. Through multiple interactions and addressing the goodness of fit by visual assessment and Pearson's chi-squared method, the best distributions that match the dataset are found by splitting the data by project negotiation (i.e. sales or rentals which indicates whether the commercial proposal contains modules that will be sold or rented) and subsequently splitting the rentals dataset into projects with 15 modules or more, and less than 15 modules, as per Eqns (4) and (5). Those distributions are added to the simulation model to calculate the duration of tasks dependent on the project size and to estimate the yearly production volume. Eqn (6) is a distribution for the quantity and likelihood of special items per project determined through the analysis of historical data and consensus from the engineering department.

$$\text{No of modules in Sales projects} = \text{LogLogistic}(1.32,\ 2.01) \tag{4}$$

$$\text{No of modules in Rental projects} = \begin{cases} \text{Weibull}(1.23,\ 2.99), & \text{if Exponential}(3.93) < 15 \\ \text{Logistic}(1.23,\ 2.99), & \text{if Exponential}(3.93) \geq 15 \end{cases} \tag{5}$$

$$\text{Quantity and likelihood of special items per project:} 0-5 = 50\% \mid 6-19 = 30\% \mid 20-30 = 20\% \tag{6}$$

Moreover, sales forecasts provided by the commercial department are shown in Table 3 and reveal the expected number of bids their sales team intends to bid followed by the conversion rate (i.e. number of bids awarded divided by total bids) on scenario-basis during a year. With the information described in Table 2 and Table 3, and with Eqns(4)–(6), a simulation model is developed in Simphony.NET to generate different scenarios for premanufacturing tasks, including the number of projects to bid on each year and the number expected to be awarded at the company under study based on the optimistic, realistic and pessimistic scenarios extracted from the simulation model.

5.1.2 Analysis of simulation output. Figure 2 depicts the performance of the company during the pre- and post-award phases by indicating the manhours required to perform tasks according to each scenario and categorised by value-added, necessary waste and pure waste as per the lean principles previously discussed. In the pre-award phase, wasteful tasks are driven by uncertain information exchanged between the company and the client wherein more information is required to fulfil the client's scope or questioned by the client during the bidding process. According to company experts, questions from clients are a common occurrence in practise since some of them lack an engineering/architectural background or are not experienced in modular construction projects. Besides sales representatives seeing this as an opportunity to prospect future business opportunities with the client, the engineering department indicates a lack in procedure to receive complete information from the start as one sales representative is more experienced than another in gathering this information. Hence, rework is required to complete the information prior to starting a new project, which may take days or may exclude the company from bidding due to deadlines imposed by the client.

In the post-award phase, necessary and pure waste occur for different reasons. Necessary waste occurs due to the changes in the project and the manual interaction with the existing ERP system, while pure waste occurs due to manual quantity take-offs and registry of special items required by the client (e.g. panic doors, curtain walls, etc.). Pure waste is significantly low at this phase due to the experience of engineers and since most of the project-related uncertainties are solved during the bid event. Table 3 indicates a higher coefficient of variation at the post-award phase where the durations are predominantly determined by project features, thus indicating that a high level of product flexibility has an impact on premanufacturing at the company under study. Additionally, in Table 4, the total times of

	Sales		Rentals	
	Number of bids	Conversion rate	Number of bids	Conversion rate
Pessimistic	174	10%	435	8%
Realistic	196	15%	490	12%
Optimistic	225	20%	563	15%

Table 3. Yearly sales forecast from commercial department

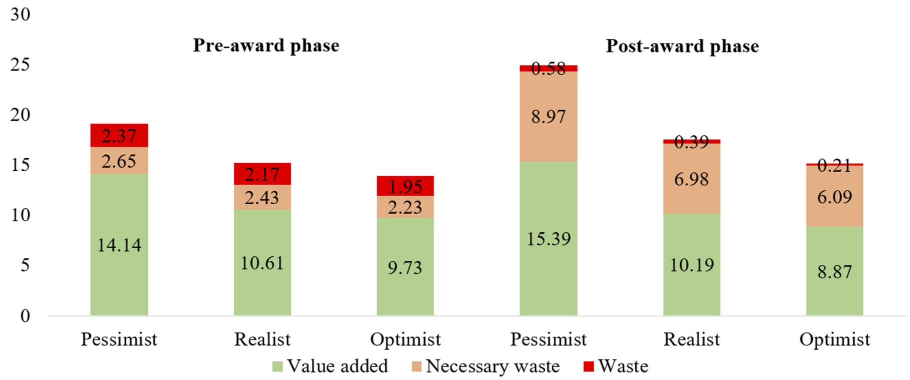

Figure 2. Pre- and post-award average manhours per project according to scenario and performance

phases are presented according to each scenario (*P*, *R* or *O*), while estimated times and coefficient of variations are calculated based on PERT analysis as per Eqns (1) and (2). The total estimated time of the pre-award phase is slightly lower than post-award, which is a positive result since it is not in the company's interest to focus on projects that may not be awarded. By digitalising and automating processes, the authors expect to reduce or eliminate wasteful tasks to decrease durations and variation in each phase.

Moreover, Table 4 presents the simulation results using the information provided by the commercial department indicating the expected number of bids accepted and rejected during a year according to information provided in Table 3. Table 4 shows a high volume of bids processed, where the conversion rate is more dependent on external factors such as market conditions and competitiveness. Although the operational staff (e.g. engineers, architects, and estimators) understand the value of upgrading and connecting their information systems by using BIM and ERP, managers are often unsure of the required investment given the short duration of projects and the low conversion rate between pre- and post-award phases. Therefore, Table 4 presents the total number of hours spent by the engineering team during the year as calculated by Eqn (3), which is used as a benchmark to measure the impact of the proposed improvements at the company. This information is very important since it quantifies the overall impact and assists managers to better plan resources for future demand.

5.2 Implementation of framework: stage 2 (design)

With the current process assessment evaluating the efficiency of mapped tasks, the authors designed improvement solutions considering the impact on tasks durations, and whether these changes are reducing waste and variation in the overall process. Different improvements were suggested and discussed during internal brainstorming sessions then mapped in the future state map to better understand its impact on the overall workflow. After consensus by the authors, suggestions were listed as improvement opportunities in three categories: (1) low-tech solutions, (2) BIM-based solutions, and (3) client-based solutions. These opportunities refer to improvements in the existing tasks listed in Table 2 that provide an estimated impact measured in saved hours or likelihood of an event occurring. Table 5 includes the improvement opportunities in each category starting from low-tech improvements and moving to the introduction of commercially available BIM software and BIM add-ons to address the specific needs of the company. For the low-tech solutions category, a checklist to capture client requirements at early stages was recommended for two reasons: (1) to help the sales team from different branches use methods to collect client requirements, and (2) to save a considerable amount of the effort required by engineering staff to acquire the information needed to fulfil the intended scope.

Under the BIM-based solutions category, the authors suggest the implementation of a BIM authoring software to enhance the design process and streamline quantity take-off for estimation and procurement. It was determined that the use of Autodesk Revit instead of using

		Scenarios			PERT analysis	
		P	*R*	*O*	Estimated total	Coefficient of variation%
Simulated total manhours	Pre-award	19.16	15.21	13.91	15.65	5.59
	Post-award	24.94	17.56	15.17	18.39	8.85
Total bids processed	Accepted bids	50	87	133	–	–
	Rejected bids	520	606	708	–	–
Hours spent in a year		9,842	12,448	15,610	–	–

Table 4.
PERT analysis on simulation results

Improvement category	Affected task	Task type	Proposed improvement	Estimated improvement (hrs)
Low-tech	More project information	Pure waste	Checklist to collect most frequent missing information from client's expectations during pre-award phase	Reduced time resulting from 50% reduction in clients questions
Low-tech	3D model and rendering development	Value-added	Acquiring a computer for renderings	50% reduced time in rendering
BIM-based	Develop 1st layout as per project specs	Value-added	Model development in BIM authoring software	0
BIM-based	3D model development	Necessary waste	Modify 3D geometry from the BIM model for rendering	1.5
BIM-based	Identification of special items and quantity take-off	Necessary waste	Create automatic schedules in the BIM model	2
BIM-based	Rework	Pure waste	More assertive modelling will reduce rework	1
Client-based	Project quantity take-off	Value-added	Add-on for generation of take-offs and company forms	4
Client-based	Revised quantity take-off	Necessary waste	Add-on for generation of take-offs and company forms	4
Client-based	Registry to ERP system	Necessary waste	Connection between BIM and ERP systems	2
Client-based	Electrical design	Value-added	Add-on for automated drawings for electrical design	1
Client-based	Plumbing design	Value-added	Add-on for automated drawings for plumbing design	1
Client-based	Openings and internal partitions design	Value-added	Add-on for automated drawings for internal partitions design	1

Table 5. Improvement opportunities for the company under study

a traditional CAD software will not affect the time required to develop the initial drawings given the time saved on later stages such as providing renderings, easier revisions, and automated schedules for quantity take-off. Apart from creating automated schedules, Revit does not provide sufficient information for modular construction practitioners and does not connect the required information with existing ERP systems. Therefore, manual work must still be done by engineers to provide the take-off required for estimation and procurement processes.

Changes in the client-based solutions category are introduced by the development of add-ons in Autodesk Revit to automate and connect the BIM model to different information systems, including the existing ERP system, and digitise the quantity take-off exercise. These add-ons are conceptualised and developed using Dynamo, while others are automated by programming directly into Revit's application programming interface. These opportunities are focused on digitising the premanufacturing processes by providing a seamless exchange of data between different design options while accelerating the procurement of special items. Other improvement opportunities in this category deal with the digitisation of the development of fabrication drawings by automating routing paths and drawing generation according to constraints provided by designers in each discipline (Table 5).

In terms of the implementation of the identified improvement opportunities, reduction of wasteful tasks is given priority to increase efficiency in the overall process. By automating these tasks, engineers no longer have to perform tedious and error-prone activities, instead, they will have more time to dedicate themselves to value-added tasks and even work on a higher number of projects. After running the updated simulation model with the proposed changes in Table 5, quantitative measures are recalculated and benchmarked for each improvement category.

5.3 Implementation of framework: stage 3 (propose and evaluate)

With results from the simulation model for the improvement opportunities proposed at the design stage, the updated measures in Eqns (1)–(3) for each improvement category are benchmarked with values from the measure stage. Figure 3 shows the estimated durations and coefficient of variation at pre- and post-award phases for each improvement category where all proposed categories outperformed the company's current state. Whether by reducing the variation in the process or the duration of wasteful tasks, significant improvements were estimated by digitising premanufacturing processes. While the low-tech solutions category reduced significantly the variation of pre-award tasks, BIM-based solutions demonstrated a significant improvement for the post-award task durations where only accepted bids are processed. The significant benefits of digitalisation were demonstrated for the client-based solutions category by automating repetitive tasks and connecting the model to the existing ERP system. The automation of quantity take-off and its connection to the ERP system reduced the duration of value-added tasks by 22% in pre-award, and the duration of necessary waste tasks by 47% in post-award, thus demonstrating significant improvements in both phases.

Moreover, Figure 4 demonstrates the overall number of hours saved in a year by improvement category in comparison with the current state for the pessimistic, realistic and optimistic scenarios, which are a function of the company's sales in a given year. This analysis is meant to quantify the potential benefits of the proposed improvements while taking into consideration uncertainties that are outside the scope of the engineering department, such as the market conditions and number of awarded proposals. As shown in

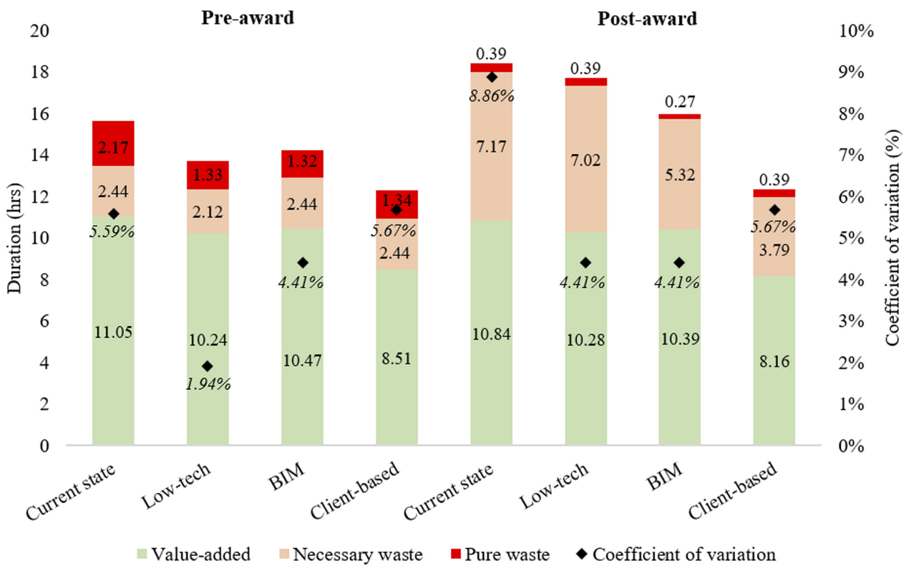

Figure 3.
Estimated duration according to each improvement category and phase

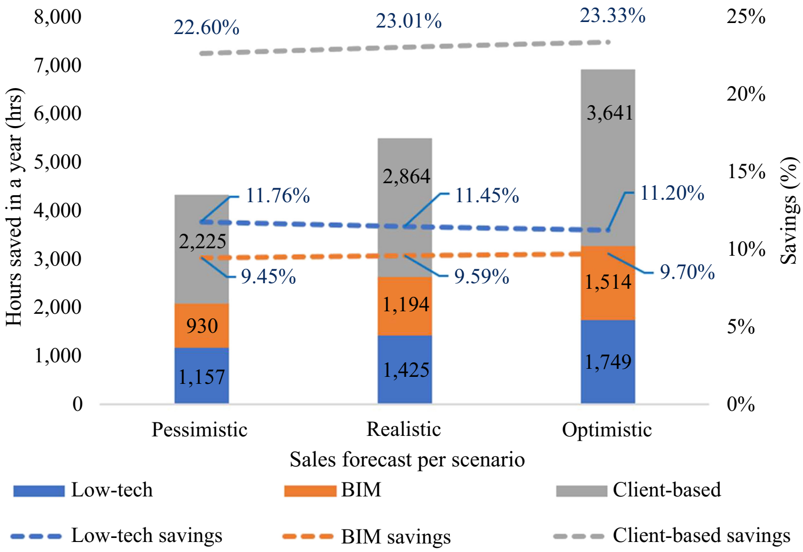

Figure 4.
Yearly estimated savings from proposed improvements

Figure 4, all categories indicate a significant reduction in hours worked, varying between 9.45% and 23.33% for the various improvement categories and scenarios. Among the improvement categories, client-based provide a significant increase in the savings compared to other categories by developing add-ons to digitise BIM processes and connecting BIM models to ERP systems. In addition to the quantitative assessment, a qualitative assessment was provided to the company that enumerates the benefits to the team such as improved communication, and readily available and easily accessible information and drawings produced by the engineering department. After the assessment was complete, the company under study selected which improvement suggestions to implement. After a period of implementation and testing, the proposed framework can be applied once again to evaluate the actual benefits of the proposed changes.

5.4 Framework evaluation and assessment

According to the DSR methodology, the evaluation of an artifact, or the framework in this case, is achieved through demonstrating their utility, quality and efficacy using well-selected methods. The assessment could be done through quantitative performance measures that can be results of satisfaction surveys (Peffers *et al.*, 2007). Accordingly, the authors have assessed the framework and its steps through a survey distributed to experts and managers that have participated directly in the practical implementation at the company. The survey requested feedback tackling the following: (1) the effectiveness of the framework to improve processes, (2) its easiness to understand and implement, (3) the sufficiency of the steps and the completeness of the framework and (4) its applicability to other offsite companies. A five-point Likert scale was used to capture responses with 1 being ‘strongly disagree’ and 5 being ‘strongly agree’. The survey had a total of five responses which included all key company experts involved at the empirical implementation of the proposed framework including the head of the engineering team, the project manager and the responsible parties for developing all mapped pre- and post-award tasks. Figure 5 demonstrates the questions, the answers from respondents and the average of responses for each question.

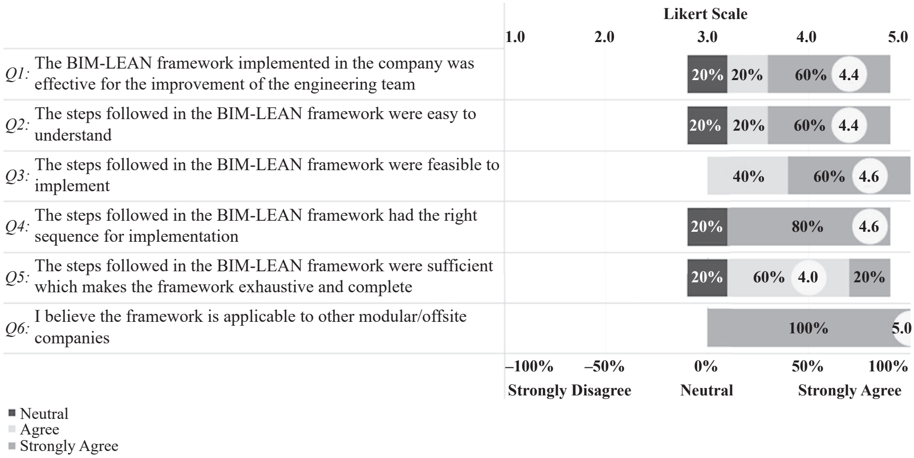

Figure 5.
Survey questions and results from the proposed framework evaluation

Results reveal that respondents saw that the framework implementation in the company was effective for the improvement of the engineering team (average answer was 4.4). As for the steps presented in the framework, respondents scored their agreement with the steps being easy to understand, feasible to implement and in the right sequence for implementation as 4.4, 4.6 and 4.6, respectively. When asked about the completeness of the framework and the sufficiency of the steps to make the framework exhaustive for applying digitalization and improvements in premanufacturing sequence, the average reply was reported as "agree"; this indicates the framework should comprehend a wider scope to digitalise processes in offsite construction premanufacturing operations. The authors, following the continuous improvement approach, would argue that not receiving a "strongly agree" on this entry is an opportunity for future investigation on other case studies. Nonetheless, a "strongly agree" response was given by all parties in reply to trusting that the framework is applicable to other modular and offsite construction companies thus concluding the proposed framework is replicable to the offsite construction industry.

In addition to validating the framework applicability and efficacy with the selected experts, informal discussions were held out while and after the implementation. Although improvements in information exchange and engineering processes have been reported, some resistance towards the multiple simultaneous changes were recorded. This indicates the need for gradual implementation of the suggested improvements for easier transition and adoption from the teams and the management. Accordingly, the authors suggest that each company shall additionally factor the time considerations into account when evaluating the set of improvements.

6. Conclusions

This study introduces a framework to evaluate processes and leverage digitalisation during the premanufacturing phases in offsite construction companies. The framework was developed to address the following main problems: (1) the misguided use of digital technologies in premanufacturing phases, where offsite construction companies are not applying the full potential of BIM and other digital technologies due to insufficient implementation procedures and guidance for connections with existing systems, (2) the shortage in measurements and quantifications of benefits and proposed improvements and (3) the poor focus of offsite construction literature on the earlier phases, where the major attention is given to the fabrication phases and production lines.

Accordingly, this study promotes the use of a stepwise framework to measure, analyze, design, propose and evaluate processes of premanufacturing phases in offsite construction companies. The novelty of this framework lies in the detailed steps and guidance provided to enhance these phases using (1) BIM potentials and (2) Lean principles, in addition to the development of methods based on (3) statistical analysis and (4) simulation for quantifying the suggested improvements. Specifically, this framework helps practitioners to quantify the benefits of integrating BIM and other information systems (e.g. ERP), thus expanding the use of BIM beyond the design stage in a practical manner based on quantitative evidence. This is achieved by providing replicable methods to promote digitalisation in offsite construction companies while providing measures to assist in its implementation and establishing a continuous improvement cycle at the offsite company. Thus, the proposed framework provides practitioners with quantitative assessment so they can discover different opportunities to improve processes through digitalisation in a structured manner. In addition to providing a quantitative assessment using the proposed measures, a qualitative assessment is also presented where intangible benefits are highlighted such as improved communication between departments and more readily available information through BIM models. Moreover, it allows processes for each offsite construction company to be evaluated while considering the peculiarity of each organisation individually.

Based on the results of a case study undertaken in a modular construction facility, 22% and 47% of tasks' durations were reduced in pre-award and post-award phases respectively, through the use of digitalisation and different improvements methods. These methods were categorized into three types: low-tech solutions, BIM-based solutions and client-based solutions. Companies invest in different methods based on the different considerations, primarily their budget and the level of improvements obtained from the diverse suggested solutions. An important understanding of this framework is the connection to lean principles that endorse solutions based on the feedback of internal and external customers to digitise processes. Simulation-based trade-off analysis and potential impacts are important considerations in the evaluation phase before selecting and implementing the improvements. The need for a learning loop and continuous improvement is highlighted in the framework.

The practical implication of the framework was also observed in a survey distributed to the main experts involved at the empirical implementation of the proposed framework. Indeed, the survey demonstrated that the majority of respondents find the proposed framework easy and feasible to implement at their context with averages of 4.4 and 4.6 in a 5-point Likert scale. Moreover, all respondents strongly agree that the proposed framework is applicable to identify and propose digitalisation-driven improvements at offsite construction companies. This indicates the readiness of the framework and its practical implementation to assist offsite construction companies to improve its premanufacturing tasks.

On a final note, the successful implementation of the framework depends on acquiring accurate information from experts working at the company. This could be a potential limitation since imprecise information will provide an inaccurate baseline for the assessment of current and future states. Hence, further work is recommended to evaluate the use of automated methods for data collection followed by methods to estimate the negative impact of inaccurate data used in premanufacturing phases in offsite construction.

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