Gholinezhad Dazmiri, D. & Hamzeh, F. (2023). A framework for design waste mitigation in off-site construction. *Proceedings of the 31st Annual Conference of the International Group for Lean Construction (IGLC31),* 1025–1036. doi.org/10.24928/2023/0119

A FRAMEWORK FOR DESIGN WASTE MITIGATION IN OFF-SITE CONSTRUCTION

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ABSTRACT

The recent global pandemic has presented unprecedented challenges to the construction industry's survival. Therefore, even minor improvements and the elimination of small sources of waste are crucial. Although they constitute a small percentage of total construction costs, hasty designs and design errors have the potential to be one of the most significant sources of waste within the industry. Also, offsite construction involves a high degree of precision and efficiency. Any waste during the design process can result in time delays, cost overruns, and suboptimal final product performance. The design process should aim for minimal waste to avoid potential delays or errors during construction or manufacturing that could lead to wasted resources and money. To address this challenge, a framework based on lean principles has been developed to minimize waste during the design process for offsite construction.

The primary objective is to incorporate lean principles and tools to address waste reduction quantitatively and measurably. Proposed solutions aim to eliminate or reduce these activities, and a framework is presented to guide organizations in mapping out the necessary steps. To assess the recommended interventions, statistical analysis and simulation methods are introduced. The framework is intended to help evaluate processes and increase efficiency during the design phase for off-site construction and built-to-order companies. The innovation of this framework lies in its precise procedures and guidance for improving these phases using Lean tools, which could provide significant benefits for off-site construction and built-to-order companies.

KEYWORDS

Off-site construction, waste, value stream, design science, simulation.

INTRODUCTION

The Architecture, Engineering, and Construction (AEC) industry is known for its dynamic nature and variability, making it challenging to achieve efficiency. As defined by researchers, efficiency is utilizing the fewest resources necessary to perform a job (Wandahl et al., 2021). In the context of Lean production and construction, the fundamental objective of efficiency enhancement is reducing waste and adding value (Koskela, 2000). The AEC industry generates substantial waste (Bølviken and Koskela, 2016). It has been utilizing Lean technologies such as Just in Time and Last Planner for the past two decades to reduce this waste.

In the context of Lean, waste refers to the improper use of time, money, or other resources due to inefficient utilization of machinery, supplies, employees, or other assets (Formoso et al.,1999). It is defined as any work or resource that does not add value to the product (Koskela, 1992). According to Womack and Jones (1996), "any activity" that consumes resources without

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adding value is considered waste in design. Time is a valuable waste indicator, particularly when assessing the proportion of non-value-adding tasks. Delays, waiting, design flaws, excessive processing, and negative iteration or rework also contribute to waste in Design (Ballard, 2000; Tzortzopoulos et al., 2020). Such wastes can significantly impact building projects, with design errors primarily contributing to cost and value loss (Tzortzopoulos et al., 2020). Rework and non-value-adding activities during the design process can also prolong the time required for design improvement and cause delays (Mryyian & Tzortzopoulos, 2013).

While many construction components are mass-produced (made-to-stock), some essential components are designed, manufactured, and delivered on demand (Build-to-order) in fabrication shops (Ballard & Arbulu, 2004) as part of the off-site construction industry. While off-site construction has many benefits, such as shorter construction times, less waste, better quality, cost-effectiveness, flexibility, and increased safety, it also has some limitations and challenges (Hussein et al., 2021), such as delayed design information receipt, frequent design revisions, altered installation timing and sequence, and demand variability (Ballard & Arbulu, 2004) and improper design work (Pasquire & Connolly, 2003).

Despite accounting for a small percentage of total construction expenses, proper design is essential for the long-term success of a project, as it affects everything from customer satisfaction to operating and maintenance expenses (Kalsaas et al., 2020). Hasty designs, design processes, and design management practices are at the root of many long-standing production and construction issues (Pikas et al., 2020). During the construction and maintenance of buildings, design errors have been the leading cause of structural failures, time and cost overruns, and catastrophic accidents (Chapman,1998; Love & Li, 2000; Love et al., 2008; Pikas et al., 2020). Rework, change orders, and preliminary estimates, resulting from poor designs, lead to overbudget spending or delays and are potentially one of the AEC industry's most significant sources of waste (Breit et al. 2008).

Several studies aim to enhance the design process in the AEC industry, focusing on integrating design with modern technology such as BIM to increase efficiency. However, there are few studies on mitigating waste in the design process, particularly in midsize and small size built-to-order plants for off-site construction. This research uses lean principles to evaluate and analyze waste in the design process, identify non-value-adding activities or processes and propose solutions to eliminate or reduce them in offsite construction. This research offers a framework for standardizing the identification and elimination of waste to assist organizations in improving their productivity and reducing costs and time. This framework addresses the challenges encountered in off-site construction and built-to-order production, including low utilization of processes, prolonged design lead times, and negative iterations. By evaluating and analyzing waste in the design process through lean principles, this framework aims to identify non-value-adding activities or processes and provide solutions to eliminate or reduce them. The proposed framework provides a transparent and standardized approach for organizations to follow in order to improve efficiency and optimize the design process in off-site construction and built-to-order production.

METHODOLOGY

The methodology adopted in this study is Design Science Research (DSR). DSR is a methodology that aims to enhance human understanding by creating new artifacts (Brocke et al., 2020). This methodology includes three steps: problem identification and objectives definition, designing artifacts to address the problem and evaluating the artifacts using a case study.

The initial step involves identifying the problem and justifying its significance, as posited by Brocke et al. (2020). To ascertain the issues that may arise during the design phase, a comprehensive review of the relevant literature was conducted, as mentioned in the last section, to identify potential problems and sources of waste.

For the second step, a case study was selected as a primary data-gathering source to better understand the design phase within off-site construction. Following an exhaustive analysis of the case study, coupled with the execution of interviews, the research objective was established to incorporate lean principles and tools to quantitatively and measurably address waste reduction. This study focused on a case study of Company X, a build-to-order offsite construction/manufacturing company in Alberta, and its design processes and procedures. To collect data, two methods were used: Semi-Structured Interviews and an Enterprise Resource Planning (ERP) database. The first method used for problem identification was structured interviews. The proposal for the study was submitted to the Research Ethics Office of the University of Alberta with all necessary information and sample interview questions and was approved by the mentioned office. Multiple interviews were conducted to understand the design process better and identify any missing information.

Along with a focus group interview with the design team, 17 interviews were conducted with the general manager, design manager, designers, production manager, order desk manager, and operations personnel. Focus group interviews are in which participants are encouraged to interact and share their thoughts and insights. A focus group interview with the design team can provide valuable feedback on the design process. It was found that the ERP system poses significant challenges and causes excessive processing time within the process. Additionally, the number of revisions due to customer feedback is high. During the interviews, the interviewees were also asked to estimate how long it would take them to complete their design tasks and the probability of rework in the design process. These probabilities can be used to estimate the system's rework, revisions, and Yield.

Data was also collected from the ERP database. There are two types of jobs based on the lead time in this process: Standard and Rush delivery. Standard delivery jobs are prioritized according to the order in which they were received, while rush deliveries are given priority in all cases, and designers begin working on them immediately. Due to their exceptional nature, rush deliveries are not included in the analysis. Based on the classification of jobs, there are four distinct categories. In retail, a customer is an individual person, and the company directly interacts. Builder, where the customers are developers and construction companies. Dealer, where the customer is typically another architecture firm or office that has utilized the manufacturing services of Company X. Lastly, Project, where the customers are primarily construction companies, and the job pertains to high-rise buildings with repetitive designs.
The duration of each step in the design process was calculated as a probabilistic distribution to reflect the actual situation more accurately.

For the third step, a robust framework was developed after consulting with the experts involved in the case study and thoroughly scrutinizing the measures necessary to identify and reduce waste. The framework specifically targets the design process, improving it through digitization and providing quantitative evidence using a simulation model. The framework employs value-stream mapping, a powerful tool for identifying and analyzing a process's current state and forecasting future processes after minimizing waste. The mapping exercise aims to identify waste areas in the design process, such as rework, multiple revisions and waiting time or latency, and provide a general guideline that outlines clear and concise step-by-step approaches for suggesting and implementing improvements to mitigate process waste.

The first stage of the framework is the definition stage, where the method of data collection and the type of information that needs to be collected as input for the process are defined. It is crucial to identify the metrics to understand how to evaluate the desired outputs and what types of outputs are expected to be controlled to identify waste. Figure 1 shows the proposed framework. The identification stage is the next step, where data is transformed, and the current situation is analyzed to find waste using value stream mapping. The way to map the value stream was adopted from Rother and Shook (1999). At the end of this stage, a simulation model was developed to get visibility into the process. The proposed framework is presented in Figure 1.

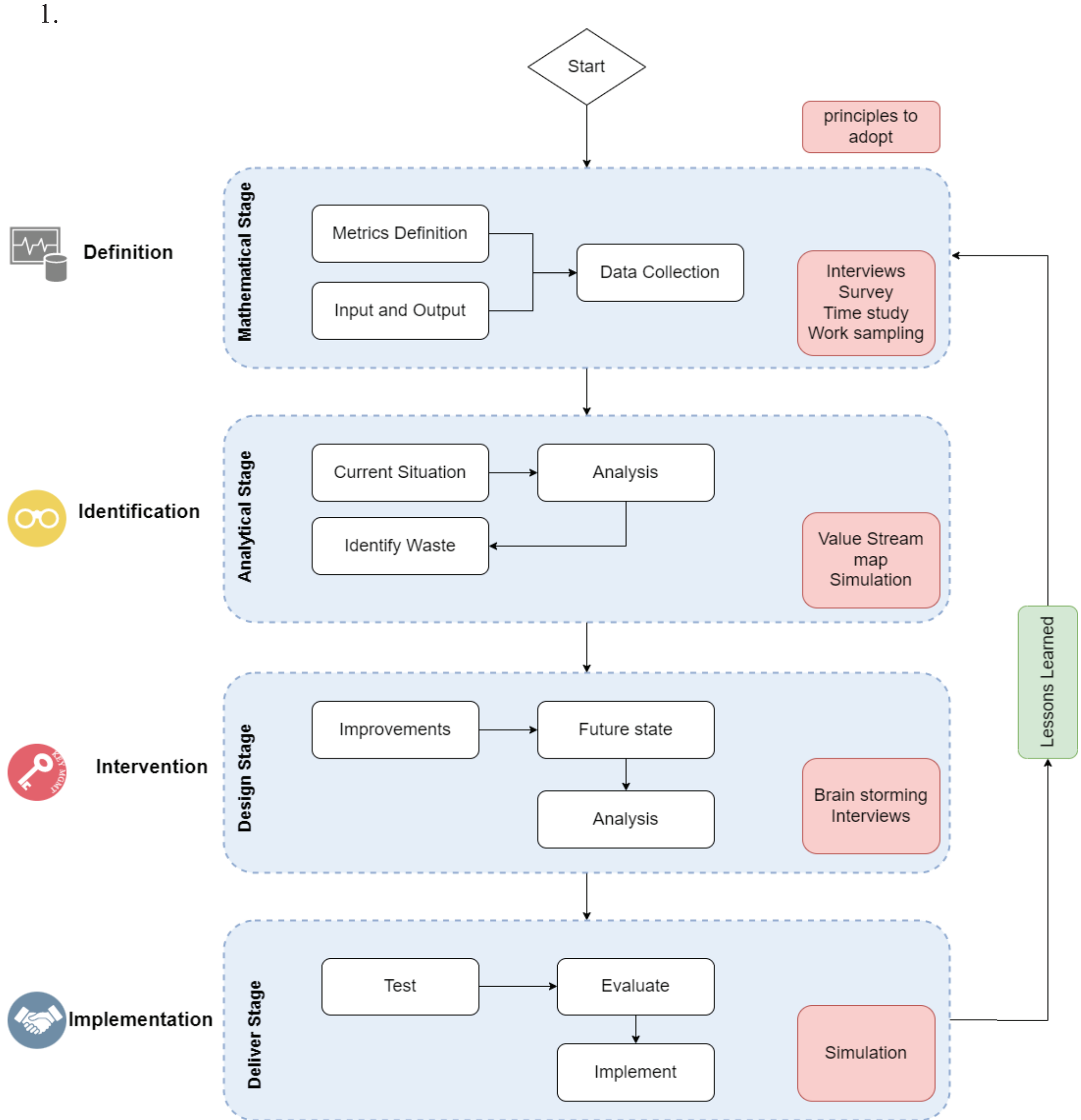

Figure 1: Proposed framework for identifying process waste.

The design stage is the third stage, where artifacts and interventions are created to address the process waste identified. At this stage, the improvements were determined by conducting expert interviews or conducting a brainstorming session with them to forecast how the process would develop in the future. The final stage of the suggested framework is to test the improvements and validate the beneficial effects on the process using the model developed in stage two. Before implementing these improvements, one must ensure their effects on the process and the organization. This can be accomplished using simulation to verify both present and potential future conditions. The company could put their improvements into practice after they are proven to be successful. This framework is generic and may also be used by others. This framework will aid and standardize efforts to boost productivity by reducing the number of non-value-adding activities.

The proposed framework reflects a comprehensive and integrated approach designed to optimize resource utilization, minimize waste, and enhance the overall efficiency of the design process in off-site construction. Statistical tools are applied to evaluate the framework, which is tested through simulation and recording of results.

Before developing the simulation model, several metrics were adopted as well to analyze the captured data. The first one was the Utilization Ratio (Equation 1), which compares the total process time (DPT) with the overall lead time (DLT). The potential for improvement in operational efficiency can be significantly increased when there is a significant difference between operational time and lead time (Berndt et al., 2016).

Another metric for assessing process performance was the Rolled Throughput Yield (RTY), which evaluates the overall performance of a process by calculating the Yield for each process phase (Graves, 2002). The Yield, or success rate, represents the percentage of units that pass through a process without defects. Rework is often an indicator of design defects. By knowing the percentage of defects per unit (dpu) for each process step, the Yield for each step could be calculated using Equation 2, and the RTY could be calculated by multiplying the Yield of each step, as shown in Equation 3.

Equation 1: Utilization Ratio = DPT/DLT

Equation 2: Yield = e ^ (-dpu)

Equation 3: RTY = Y_1*Y_2…*Yn

Because the time required to complete a task varies depending on the designer and job, the data must be fitted to specific distributions to calculate task duration. These distributions can be computed using software such as EasyFit and evaluated using the Kolmogorov-Smirnov (K-S) test.

The simulation validated the design process's current state and evaluated the proposed intervention's impact. Once validated, simulation was used to evaluate the impact of each proposed intervention and its combinations. Simphony.Net 4.6.0 was used to develop the simulation model and test the improvements to the design process. The simulation model was generated based on the general template and elements of the Simphony, presented in Figure 2.

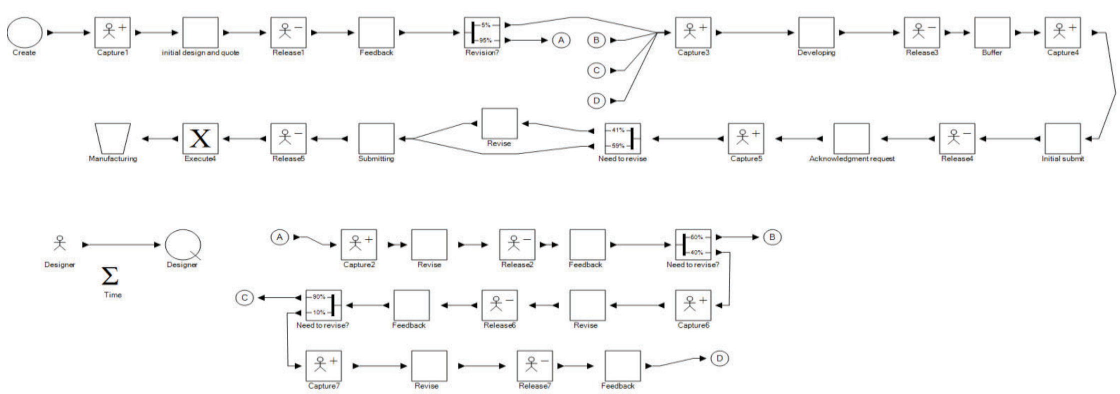

Figure 2: The general layout of the current state map simulation

Multiple approaches were used to verify that the model accurately represents the target concept to ensure the created simulation model's accuracy. These approaches were based on the methodologies proposed by Al-Hattab and Hamzeh (2018) and included verifying the consistency of input and output data, monitoring the logical performance of the model through basic indicators, and making the appropriate modifications to ensure an accurate simulation. Through the monitoring of these approaches, it was determined that the model was correctly implemented. Additionally, the case study model, its input and output, were presented to experts for validation. It was confirmed that the simulation results accurately reflect the real-world process being studied. It is important to note that while the simulation results indicate a significant reduction in design lead time, the research method has limitations, and the results should be interpreted with caution.

RESULTS

From the data collected, it has been determined that, on average, the initial designs require 2.5 revisions. The probability of the design being revised for the first time is 95%, and for the second time, 45%. During the interviews, the interviewees were also asked about the challenges and threats in the design process that could cause waste or non-value-added activities in the system. Table 1 shows the results from the interviews regarding the task durations.

Table 1: Task duration results from interviews

Task	Unit	Time			
		Optimistic	Most probable	Pessimistic	Average
Designing the initial designs and quote package	hours	2.44	3.4	5.8	3.63
Getting feedback from the client	days	2.2	4.2	10	4.83
Revising the designs based on the feedback	hours	1.3	2.3	4.4	2.48
Revising the designs a second time	hours	0.5	1	2	1.08
Developing final package	hours	1.2	2.4	4.2	2.5
Reworking because of the initial blueprint	hours	1	1.7	2.8	1.77
Generating the contract	hours	0.45	0.7	1.05	0.71
Building the file in the ERP	hours	0.3	0.45	0.85	0.49
Receiving feedback from the control department	days	2.8	4.2	6.6	4.37
Making final changes based on an acknowledgement	hours	0.3	0.6	1	0.61
Submitting final copy	hours	0.35	0.55	1.1	0.60
The whole design process	days	16.4	47.3	106.4	52

The proportion of each delivery type can be seen in Figure 3, and general information on each class is summarized in Figure 4.

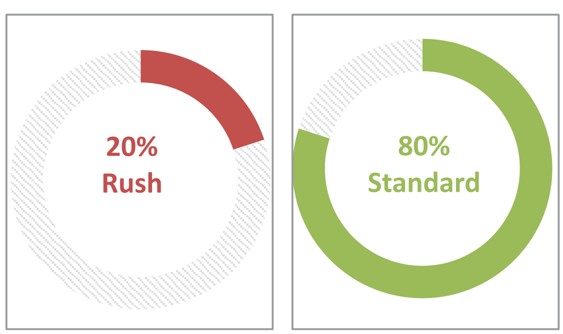

Figure 3: Type of job delivery in Company X

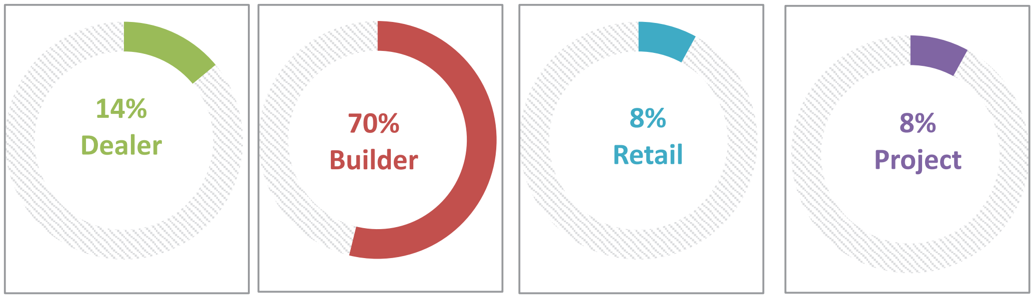

Figure 4: Available data on each job category

Upon completing the current state map, evaluating the parameters identified for value stream mapping is essential. The first parameter to evaluate was Design lead Time (DLT) and design process Time (DPT) which were 50.74 and 4.16 days, respectively. Using these two parameters, the Utilization Ratio is 8.2%. The rolled Throughput Yield (RTY), calculated using Equations 2 and 3, is 13.95%.

The case study highlights the need to improve the design system and process to increase efficiency. These improvements can be made at three levels: the designer level, the organizational level, and the client level. Addressing waste at the designer level is the most targeted approach, while organizational-level improvements require a coordinated strategy and may involve higher costs. Lastly, addressing client waste is crucial to improving the overall design process. Table 2 summarizes the suggested interventions to improve the system and process.

Table 2: Suggested improvements for the case study

#	Interventions	Related Challenge	Improvement
1	Reducing negative iteration	Insufficient information	Client
2	Reducing the waiting time	Waiting time	Client
3	Increasing Yield in the initial submission	Design errors	Designer
4	Levelling the process	Workforce	Organization
5	Reduce the redundancy associated with	Redundancy in the process	Organization
6	Using new drawing software	Drawing software restrictions	Organization
7	Reducing acknowledgment waiting time	Waiting time	Organization
8	Reduce buffer time after the contract	Buffer	Designer

The scenarios for the system's future state were developed by incorporating the interventions outlined in Table 3. Initially, individual interventions were simulated. However, as there is potential for more significant improvements, Intervention Combinations (IC) were constructed by combining two, three, four, and so on, up to eight interventions. It should be noted that due to the complexity of the existing system, it may be difficult to implement multiple interventions simultaneously. A total of 255 ICs were constructed and simulated to evaluate the system under different conditions. The simulation results indicate that implementing multiple interventions results in a more remarkable improvement in the design process. The combination of all eight interventions shows the most significant improvement, with a 47.3% reduction in design lead time and an increase in utilization ratio to 13.7%. This highlights the importance of considering a holistic approach when implementing changes in the design process. Table 3 shows the most significant reductions in DLT, and Figure 4 also shows the DLT for different interventions.

Table 3: Simulation results for intervention combinations based on DLT reduction.

Intervention Combinations	DLT (days)	Utilization	RTY
1&2&3&4&5&6&7&8	27.79	0.137	0.39
1&2&3&4&6&7&8	27.99	0.136	0.39
1&2&4&5&6&7&8	28.35	0.134	0.26
1&2&3&4&5&6&7	29.64	0.128	0.39
1&3&4&6&7&8	29.65	0.128	0.39
1&2&3&4&5&7&8	30.28	0.132	0.39
1&3&4&5&6&7&8	30.3	0.125	0.39
1&2&3&4&6&8	30.4	0.125	0.39

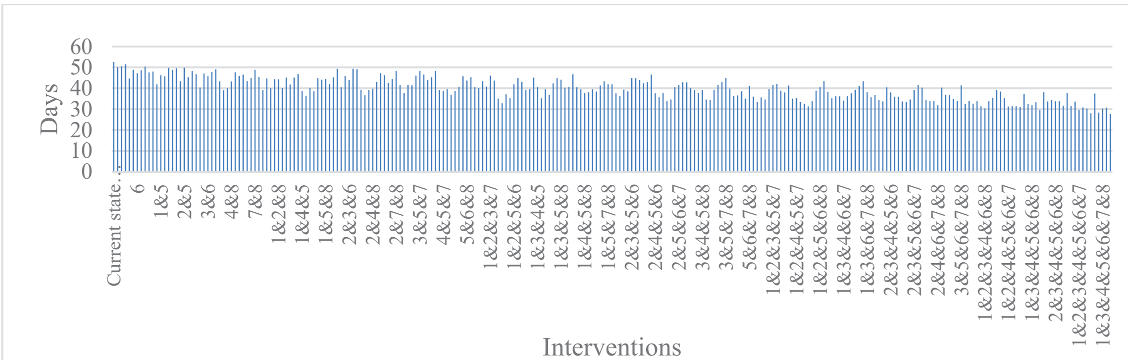

Figure 5: Design Lead Time for suggested interventions

The value classification pr project for the current state situation and implementing eight interventions is presented in Figure 5, showing a considerable improvement in reducing non-value-adding activities.

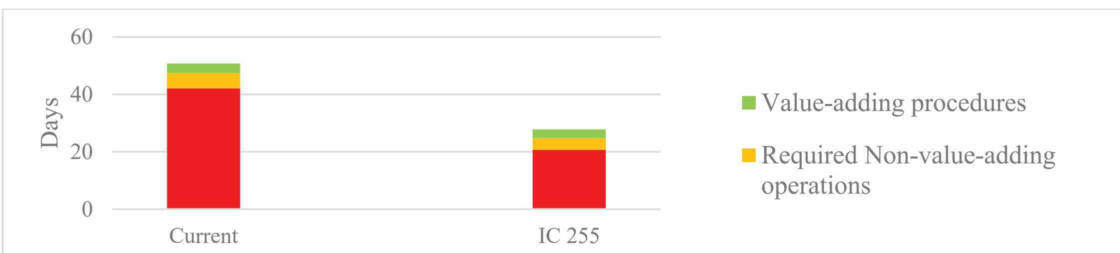

Figure 6: Value classifications per project

DISCUSSION

After eliminating irrelevant data and information, the Value Stream Mapping (VSM) was performed. As previously stated, VSM helps to gain a more comprehensive understanding of the process. The first parameter to evaluate is the average Design Lead Time (DLT), which is 50.74 and Design Process Time (DPT) is calculated to be 4.16 days, which shows that if there was no disruption in the flow of information, design jobs should go through the whole process in only 4.16 days. Compared to the time it takes to go through the process, the Utilization Ratio is found to be 8.2%, indicating that only 8.2% of the time allocated for design is used for the actual design process. While the time buffer in the process may be attributed to a designer's workload, the utilization rate of 8.2% is still deemed insufficient.

Another critical parameter to calculate is RTY, calculated by considering the number of reworks and revisions required for each job and is used to determine the Yield for each station.

As per the calculation, only 14% of design jobs pass the process without defects. This low percentage indicates room for improvement in the design process to reduce reworks and revisions.

Numerous iterations between the customer and the designers often hinder the design process. This can be caused by a lack of clear direction from the client or inadequate information from the marketing team. Communication gaps and requests for minor design changes between designers and other departments also contribute to this challenge. Currently, revisions in the design process are a source of waste. It is essential to focus on creating more value in the initial design to reduce the number of revisions.

One of the significant challenges identified in the interviews is using the ERP system. The system is difficult to navigate and was not explicitly designed for this company. Additionally, the requirement to upload information to the ERP system and an internal server results in redundant work. This causes difficulties for designers and other employees in making changes and updating information.

Customization refers to the process of creating a product that is tailored to a specific customer's needs or preferences. This can include unique designs or patterns that are difficult to produce. All departments in the manufacturing process can face challenges when it comes to customization, particularly in areas such as design, sourcing unique materials, and production. Designers may not have the specific knowledge or skills to create the custom design that a customer requests. Finding unique materials or colours can be difficult, and purchasing small quantities can be costly. Specialized machinery and operators may be required in production, causing disruptions and increasing costs. Additionally, the production of custom designs may require more time and effort, resulting in longer lead times. To minimize these challenges and save time and money, it may be more efficient for the company to reduce variability and avoid customization by focusing on producing standard products.

The proposed interventions were simulated to assess their potential impact on the design process. The simulations included individual interventions and combinations of up to eight interventions. The results of the simulations show that levelling the process and implementing new drawing software and generative design approaches have the most significant potential to improve the design lead time, resulting in a 15% reduction in DLT and a 17% increase in the utilization ratio. Additionally, interventions 1 and 3 effectively reduced rework and increased Yield, as evidenced by improvements in RTY.

It is anticipated that the implementation of all interventions will result in a reduction of time for not only non-value-adding activities but also required non-value-adding and value-adding activities. This presents an opportunity to optimize the system and increase efficiency.

This study validated the proposed framework and interventions by surveying the company under examination. A 5-point Likert scale was utilized in the questionnaire to gather feedback on the effectiveness and applicability of the interventions, with scores ranging from 1 (very poor) to 5 (excellent). The results of the survey are presented in Table 4.

Table 4: Survey results for evaluating the effectiveness and applicability of interventions.

Interventions	**Effectiveness**	**Applicability**
1: Reducing negative iteration	4	3
2: Reducing the waiting time for feedback	3.5	3.5
3: Controlling the designs	4.5	4.5
4: Add additional designers as needed	4	3.5
5: Reduce the redundancy	4	4
6: Using new drawing software	4.5	3
7: Reduce waiting time for the Order desk	4.5	3.5
8: Reduce buffer time after the contract	4	3

Overall, the proposed interventions effectively reduced waste and improved the design process. However, there are some concerns regarding implementing specific interventions, such as collecting customer feedback in a timely manner and the unfamiliarity of designers with new software. These concerns can be addressed through further training and education to ensure the successful implementation of the proposed solutions. Additionally, reducing the invoice validation period may be challenging and requires further examination to identify ways to reduce the buffer time after the contract effectively.

CONCLUSIONS

This research aims to develop a methodology to improve the design process by identifying and eliminating waste and non-value-adding activities. This research primarily employs value stream mapping as the method of investigation and simulation to evaluate the proposed improvements. Various methods were employed to gather data on the duration of each task in the design process and to provide a statistical overview of the process.

The proposed framework aims to provide organizations with a systematic approach to identifying and addressing waste in the design process. The framework utilizes various Lean tools and methodologies, such as statistical analysis and simulation, to evaluate and improve the efficiency of the design phase in off-site construction and built-to-order companies. The simulation results indicate a significant design lead time and utilization ratio improvement due to implementing the proposed interventions. However, it is essential to note that further cost reduction can be achieved by implementing additional Lean tools. The proposed framework is validated through an evaluation process, which compares the stated objectives to the actual outcomes of its implementation and may employ various evaluation procedures depending on the context and topic being assessed.

The objective of identifying waste in the design process in build-to-order off-site construction/manufacturing was achieved using value stream mapping as a Lean tool. This process-oriented approach allowed for the study and evaluation of the system, focusing on identifying and eliminating waste and non-value-added activities. In addition to value stream mapping, interviews and simulations were used to gather information and gain insight into the design process. These methods provided a comprehensive understanding of the process, enabling the identification and elimination of waste, ultimately leading to an improved design process.

In the case study context, additional issues required more comprehensive managerial solutions. These issues were rooted in the high level of customer involvement in the design process, which resulted in increased variability and a need for rework. This challenged the designers and made it difficult to standardize the design process.

The limitations of this research should be acknowledged. One limitation is that the data collection method used was interviews with a limited number of experts, which may not fully represent the entire population. The study did not consider the participants' demographic characteristics, which could have provided more results. Furthermore, only a few process classes were mapped using value stream mapping, which may not have captured the full scope of the process. Additionally, the metrics used to monitor waste were limited to time and reworked, and other factors could have been beneficial for identifying hidden waste within the process. Furthermore, the proposed interventions were based on the availability of technology for small and medium-sized businesses, and future research could benefit from evaluating other interventions and their impact on the design process. Finally, future research could explore the development of a digital platform or dashboard to integrate all design processes and tools, including enterprise resource planning (ERP) and design software, which could aid professionals in reducing waste and increasing value delivery.

REFERENCES

Al Hattab, M., & Hamzeh, F. (2018). Simulating the dynamics of social agents and information flows in BIM-based Design, *Journal of Automation in Construction*, 92: 1–22. https://doi.org/10.1016/j.autcon.2018.03.024

Ballard, G. (2000) The Last Planner System of Production Control. Ph.D. Thesis, The University of Birmingham, Birmingham, UK. Available at: https://Leanconstruction.org/uploads/wp/media/docs/ballard2000-dissertation.pdf

Ballard, G. & Arbulu, R. (2004). *Making prefabrication Lean*. In Bertelsen, S. & Formoso, C. T. (Eds.), 12th Annual Conference of the International Group for Lean Construction. Helsingør, Denmark, 3–5 Aug 2004. Available at: https://iglc.net/Papers/Details/285

Berndt, R., Silva, N., Caldera, C., Krispel, U., Eggeling, E., Sunk, A., Edtmayr, T., Sihn, W., & Fellner, D. (2016). VASCO - Mastering the Shoals of Value Stream Mapping. https://doi.org/10.13140/RG.2.1.1343.0646

Bølviken, T. & Koskela, L.J. (2016). Why hasn't waste reduction conquered construction? 24th Annual Conference of the International Group for Lean Construction, Boston, MA, USA. Available at: www.iglc.net

Breit, M., Vogel, M., Häubi, F., Märki, F., & Raps, M. (2008). 4D design and simulation technologies and process design patterns to support Lean construction methods. *Journal of Tsinghua Science and Technology*, 13(1), 179–184.

Brocke, J., Hevner, A. & Maedche, A. (2020). *Introduction to Design Science Research*. *In* Brocke, J., Hevner, A., Maedche, A. (eds.), Design Science Research: Cases. Progress in IS. Springer, Cham; pp.1–13.

Chapman, J. (1998). Collapse of the Ramsgate walkway. *Journal of Structural Engineering*, 76: 1–10.

Formoso, C.T., Isatto, E., & Hirota, E. (1999). Method for waste control in the building industry. *In* Proceedings, 7th Annual Conference of the International Group for Lean Construction. Berkeley, California, USA, 26–28 July 1999. pp. 325–330, Available at: https://www.researchgate.net/publication/228646326

Graves, S. (2002). Six sigma rolled throughput yield. *Journal of Quality Engineering*, 14(2): 257–266.

Hussein, M., Eltoukhy, A., Karam, A., Shaban, I. & Zayed, T. (2021). Modelling in off-site construction supply chain management: A review and future directions for sustainable modular integrated construction, *Journal of Cleaner Production*, 310: 127503. https://doi.org/10.1016/j.jclepro.2021.127503.

Kalsaas, B.T., Rullestad, A., & Thorud, H. (2020). Continuous improvement on detailed design phase: A process perspective. *Journal of Engineering, Project, and Production Management*, 10(2): 103–113

Koskela, L. (1992) Application of the New Production Philosophy to Construction, Center for Integrated Facility Engineering, Department of Civil Engineering, Stanford University. Technical Report number: 72.

Koskela, L. (2000). An Exploration towards a Production Theory and Its Application to Construction. Ph.D. Thesis, VTT Technical Research Centre of Finland, Espoo, Finland, 2000.

Love, P.E. & Li, H. (2000). Quantifying the causes and costs of rework in construction. Construction Management and Economics, 18: 479–490.

Love, P.E., Edwards, D.J., & Irani, Z. (2008). Forensic project management: An exploratory examination of the causal behavior of design-induced rework, IEEE Transactions on Engineering Management, 55: 234–247.

Mryyian, M. & Tzortzopoulos, P. (2013). Identifying sources of design errors in the design of residential buildings. International Group for Lean Construction (IGLC), Fortaleza, Brazil. https://doi.org/10.13140/2.1.4038.7843

Pikas, E., Koskela, L., & Seppänen O. (2020). Improving building design processes and design management practices: A case study. Sustainability, 12(3): 911. https://doi.org/10.3390/su12030911

Pasquire, C.L., & Connolly, G.E. (2003). Design for manufacture and assembly. *In* 11th Annual Conference of the International Group for Lean Construction, Virginia, USA. Available at: https://iglc.net/Papers/Details/263

Rother, M., & Shook, J. (2003). *Learning to see: Value stream mapping to add value and eliminate Muda*. Cambridge: Lean Enterprise Institute.

Tzortzopoulos, P., Kagioglou, M., & Koskela, L. (2020). *Lean Construction, Core Concepts and New Frontiers*. New York, Routledge.

Wandahl, S., Neve, H. H. & Lerche, J. (2021). What a waste of time. *In* Proceedings, 29th Annual Conference of the International Group for Lean Construction (IGLC). Lima, Peru, 14-16 July 2021; pp 157–166.

Womack, J., & Jones, D. (1996). Lean Thinking: Banish Waste and Create Wealth in Your Corporation, Journal of the Operational Research Society 48(11), https://doi.org/10.1038/sj.jors.2600967.