Improvement of Masonry Construction Site Conditions Using Lean Principles

by

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Abstract

Construction site conditions are suboptimal and current practices generate a lot of waste in all its forms (material, equipment, resources, etc.), hindering the true potential of productivity and value generation on construction sites. Lean Construction research studies oriented toward improving site conditions are available, focusing on specific aspects of waste. Nevertheless, there is still a gap in improving construction flow research, both at the micro and macro levels.

This study presents a framework to analyze and optimize construction site conditions. The concept developed in the framework is rooted in Lean Thinking and Theory. A case study of the masonry construction process is performed to test and validate the framework. The different types of walls using masonry construction as a construction method were compiled and presented.

Lean tools were used in this case study, namely Value Stream Mapping and Simulation Modelling, to study the performance of the current masonry construction practices on construction sites. Bottlenecks in the current process were identified, and a base-case scenario was proposed with potential solutions; extracted and analyzed metrics included: construction lead time, daily productivity, and station utilization. Subsequently, the use of modular construction, interlocking masonry blocks and a robot platform were proposed as solutions for improving construction site conditions. These three systems were studied and analyzed using Simulation Modelling compared to the traditional masonry construction process. Each solution was shown to partially remediate some problems encountered in traditional masonry construction practices. Modular construction improved scheduling issues, whereas the interlocking blocks could solve the problematic use of mortar. The robot platform and arm would remediate the problems of waste related to material handling on site.

In conclusion, this study analyzed the construction systems, both at the micro and macro levels. Simulation Modelling showed that combining three interventions: modular construction, interlocking blocks, and a robotic platform, could substantially decrease waste while increasing generated value. This case study sets the ground for the future adoption of automated/robotic technology in Lean Construction Engineering.

Preface

This thesis is an original work by Karl Keyrouz. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "A Framework for Improvement of Construction Site Conditions Using Lean Principles", No. 00133067, August 09, 2023.

Some of the research conducted for this thesis forms part of a research collaboration led by Professor Farook Hamzeh at the University of Alberta with Associate Professor Carlos "Lobo" Cruz Noguez at the University of Alberta. Interventions 1 and 2, referred to in Chapter 8, were developed by the research group of Dr. Cruz Noguez. Chapters 1,2,3,4,5,6,7 as well as simulations for all interventions and their analysis in Chapter 8 and Chapter 9 are my original work.

Dedication

To the memory of my beloved father, Nader, who left us too early…
His unconditional Love, Resilience, and Wisdom
will always enlighten my Life!

Karl Nader Keyrouz

Acknowledgements

I would like to express my most sincere gratitude to my advisor, Pr. Farook Hamzeh, for his excellent guidance and unwavering support. His immense knowledge and passion for Lean Construction inspired me throughout this journey and shaped my career forever!

I would like to acknowledge the construction site staff for their kindness and patience. Their help and input were truly invaluable!

Finally, THANK YOU to my little family,

Pascale, my mother and Jean Louis, my brother

for always being there for me!

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1. Introduction

1.1.Background

Since the early developments of civilization, masonry has been used as a construction material to create a habitat for early humans. This art of building by crafting, stacking, and joining units has gradually evolved over time. Throughout Middle Ages, stones, clay, and later concrete were used with the addition of mortar to build walls faster. In modern times, masonry is still used as a material for residential but also industrial and commercial construction buildings. Its use in many construction areas stems from its versatility, durability, and aesthetics. Nowadays, masonry blocks come in many forms: clay blocks, veneer masonry, stone masonry, etc. However, concrete masonry units (CMUs) are currently Canada's most common type of masonry blocks.

Masonry construction is a process by which CMUs are used to build structural elements in residential, industrial, and commercial construction. Labour productivity represents a significant issue in the construction industry; it can be variably affected by direct and indirect factors pertaining to the workers, the site environment, the materials, and the equipment used, in addition to managing all these variables (Singh & Kumar, 2021). Moreover, like any construction process, masonry construction has suffered from productivity issues (Bokor et al., 2021), negatively affecting construction site costs, schedules, and resources. Factors affecting productivity are inherently complex, and current models fail to capture all these. Hence, the need to constantly create new frameworks and prediction models encompassing new factors such as the worker's experience (Khanh et al., 2023), physical stress (Aliasgari et al., 2022) or sleep quantity (Sharath & Loganathan, 2022).

Lean construction is defined as a philosophy where the value in a process is maximized for its stakeholders. It also revolves around the idea of reducing waste, improving efficiency, and reducing variability in a process. Architecture, Engineering, Construction (AEC) has been suffering from a lack of innovation (Hamzeh et al., 2021), and masonry construction has been exhibiting the same issues as other types of construction, such as absenteeism, delays, and lack of skills (Porntepkasemsant & Charoenpornpattana, 2015), affecting construction productivity.

The masonry construction process in this thesis is limited to CMUs as defined by Canadian Standards Association (CSA) CSA A165 and CSA S304.1. For these units, CSA A165 defines hollow, semi-solid and solid units, and CSA S304.1 defines structural design standards for masonry construction. Both these codes influence the physical properties of the CMUs, which will affect the way masonry construction happens on site. Physical properties (such as the type) of CMUs are essential to consider in the study since different types of blocks will require additional effort to be laid, as they will generate a different amount of stress by the worker on the construction site. As a construction material, CMUs are used concurrently with mortar when construction is in process, and the two are closely linked regarding the dynamics of a construction site from labour, material, and equipment perspectives.

The work undertaken in this thesis belongs to the production system design research. The research framework developed in this thesis is rooted in lean principles and lean construction practices. Lean research methods and tools were used in the identification of value-adding areas on construction sites. Simulation Modelling, as a tool, has been used in tandem with lean tools to increase value for construction site conditions. This thesis provides a new framework for reducing variability in construction processes and tries to identify all sources of waste from a material, labour, and equipment perspective to devise optimal solutions to remediate such sources of waste. The masonry construction process is first evaluated as a case study in its present conditions. It is used as a benchmark for possible lean solutions that will impact the steps undertaken on-site for masonry construction, ultimately improving construction site conditions.

Waste in all its forms, whether related to material, equipment, or labour, must be tackled to get optimal results and enhance construction site conditions.

1.2. Problem Statement

Current systems tend to concentrate on specific aspects of masonry construction rather than considering ways to accurately improve and reform the construction process on both micro and macro levels. Indeed, studies performed to improve masonry construction always considered entire rows (Melo et al., 2017) rather than the parts and steps that constitute the masonry process as a whole. Moreover, contemporary masonry construction practices are still time-consuming and physically strenuous for workers, which may affect the true potential of productivity on construction sites. The strenuous nature of the work leads to poor retention rates in the industry after five years of experience and an increase in musculoskeletal disorders, negatively affecting the health of journeymen and construction workers (Alwasel et al., 2017). These problems lead to the emergence of current and ongoing studies in construction site developments focused on autonomous systems where the workers' role is limited. Indeed, the development of automated systems using cable robots (Bruckmann & Boumann, 2021) is underway. However, current research and systems being developed with the goal of full automation cannot be implanted yet due to current industry challenges, such as the complexity of a dynamic construction site and the nature of the systems to be developed (Howe, 2000; Ardiny, 2015). These limitations resulted in the development of semi-autonomous systems where robots are used in masonry construction, such as a levelling pallet (Ryu et al., 2020). Nevertheless, current research does not look at improving masonry construction practices considering the development of new construction systems. To address these challenges, it is necessary to look for ways that can improve masonry construction that seeks to address the different problems found on a construction site concerning masonry construction, all while considering the various steps taken in masonry construction.

1.3. Research Questions

- How can masonry construction site conditions be studied to pinpoint the different areas in need of improvement?
- How can different lean tools and lean thinking be used to improve masonry construction site conditions?

1.4. Research Objectives

- Investigate the most common patterns of shear masonry walls and derive their deltas from a lean perspective.
- Identify bottlenecks in masonry construction activities performed related to a typical horizontal shear masonry wall using Value Stream Mapping and Simulation Modelling.
- Develop a framework to reduce the waste related to construction lead time and compare productivity for proposed new construction systems.

1.5. Methodology

The methodology used in this thesis is Design Science Research (DSR) which consists of three steps: (1) problem identification, (2) Framework Development and (3) Framework Evaluation.

1.5.1. Problem Identification

In the problem identification step, the current state of masonry construction is studied to identify the challenges faced daily on construction sites. In this first step, data is collected in a myriad of ways, namely video recordings, interviews, and construction site visits. The first step is crucial in understanding the subsequent steps and research to be taken.

Current construction research focuses on improving specific metrics within a particular process (productivity, fatigue, etc.) rather than looking at ways to improve the process more holistically. Very little research looks at improving construction in a hybrid (human-robot collaboration) way but instead focuses on full automation, which may not always reflect the realities on the ground.

1.5.2. Framework Development

Having identified the problem, developing a framework to tackle it is necessary. The framework employs the use of lean theory and lean construction practices. Moreover, it encompasses the tools used in the research to solve the problem identified at hand. From this point of view, it is possible to determine what is value-adding and non-value adding from a lean construction point of view on a construction site. The framework's primary goal is to reduce waste and variability and increase value in a construction system.

After data collection, a Value Stream Map is created to identify all the on-site steps and focus on the areas with the most waste. The relationship between information and material flow on the construction site is established in this stage. Having established a Value Stream Map, a simulation model is built to better understand the current production system on the construction site and predict the behaviour of the existing systems on the construction site. Simulation

Modelling is used to understand better the effects of different proposed solutions (from a lean perspective) if they were to be implemented on a construction site. Having done the simulation, the results are analyzed, and lean improvements are proposed. The proposed lean improvements would be tested using simulation models to assess the extent of the effect these lean improvements have on the entire system. The system is finally evaluated using feedback from industry practitioners to align academic and research contributions of the developed framework following evaluation.

1.5.3. Framework Evaluation

In this last step, the framework is evaluated using data collected from construction sites where CMUs are being laid using what will be referred to in this research as the "traditional masonry construction process. Feedback concerning the lean improvements is taken from the construction site's superintendent, where the data collection was performed to improve the framework. Figure 1 shows the Research Framework adopted in this thesis:

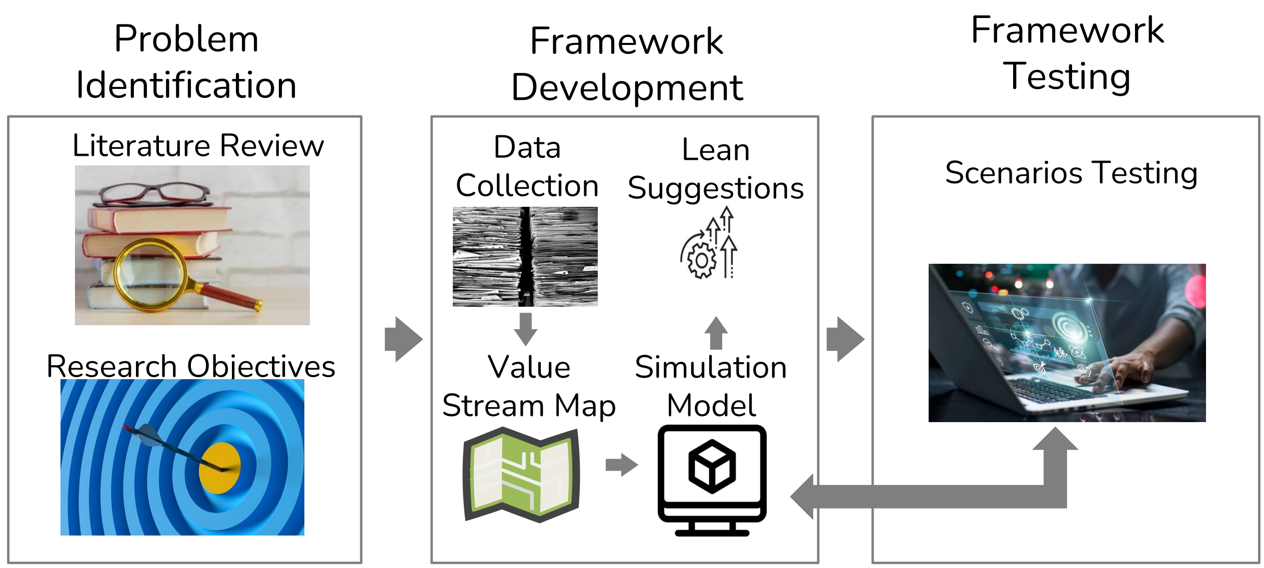

Figure 1: Research Framework according to DSR

1.6. Organization of Thesis

This Thesis is composed of 9 chapters. Chapter 2 presents the research methodology adopted by explaining in detail the steps of the artifact (the framework) developed. Chapter 3 presents a thorough literature review on lean thinking and subsequent tools used in the study (Value Stream

Mapping, Simulation Modelling). Chapter 4 presents an overview of the different types of masonry walls and their deltas from a lean perspective. Chapter 5 elaborates on the case- study chosen to test the framework developed in this study. Chapter 5 also proves all the methods used for data collection for the case study. Chapter 6 presents the steps used to create a value stream map of the current masonry construction process on site. Chapter 7 presents the simulation model for the base-case scenario of the masonry construction process, its development, validation, and verification. Chapter 7 also provides the metrics analyzed based on the simulation model and the results of the simulation model. Chapter 8 presents three different possible lean interventions and the results obtained when simulating the incorporation of these interventions into the masonry construction process. Finally, Chapter 9 presents a conclusion of the study, its limitations, and the potential for future research.

2. Research Methodology

This chapter explains the research methodology adopted in the study and describes the data collection methods and tools used to improve construction site conditions.

2.1. Design Science Research

As previously stated in Chapter 1, Design Science Research (DSR) is the methodology used in the study presented in this thesis. Smith (2015) applied DSR in a lean setting and found it to be an effective research tool due to the iterative nature of DSR, which suits lean thinking. Hence, the use of DSR to improve construction site conditions can be considered useful since the reduction of waste in its different forms stems from lean philosophy in its essence. The main objective of DSR is to establish robust and practical solutions to current problems faced in the industry and real-world settings while still being rooted in theory (Brady et al., 2013).

DSR was chosen to improve construction site conditions due to its versatility as a research method. DSR would allow us to develop a framework which enables the increase of value delivery on construction sites, all the while decreasing generation on construction sites.

2.2. Problem Identification

Value generation and waste reduction are essential factors in any construction project and, by extension, construction site conditions. Excess waste in all its forms leads to failure on construction sites. This failure translates into schedule delays, budget and cost overruns and excess material waste. As a research methodology, the first step in DSR is problem identification.

2.2.1. Literature Review

2.2.1.1. Introduction

The first step undertaken in this research study is Literature Review. It is a crucial component of any academic study and involves gathering existing works and research in a specific field. It serves as starting point for topic selection and research investigation. Literature Review helps identify the gaps to formulate and develop a research question for study and analysis. The Literature Review conducted in this study has the objective of understanding the current tools being used in academic research to improve construction site conditions (lean principles, Value Stream Mapping, Simulation Modelling, etc.) and find a gap in the research that enables us to come up with a research question to study.

2.2.1.2. Purpose

Literature review, as a research method, has many purposes. It enables researchers and scholars to obtain knowledge about a particular topic, delve further into specific aspects, and gain a deeper understanding of the current advancements in the studied field. In our case, a literature review enables us to know what has previously been done to improve construction site conditions and ensure that subsequent research is well-placed within current and existing scholarly discourse and research. Literature review enables us to further contribute to scholarly advancement in construction. By analyzing current research trends, we can clearly understand the existing knowledge gaps on which we can base our research. Moreover, examining current limitations in current scholarly work enables us to formulate a problem to tackle and ensure that the contribution to the scientific body of knowledge is valuable, relevant, and logical.

2.2.1.3. Approach

A literature Review can be done in a myriad of ways, and each is applied to suit the need and objective of the research at hand. The approach in this research involves searching for current improvements to construction site conditions from different aspects (such as productivity, fatigue reduction etc.) and analyzing the results to identify the gaps. The literature is scoured for relevant sources (such as models currently analyzing problems affecting construction sites, productivity, etc.) and organized. Finally, the literature is collected, synthesized, and critically evaluated to determine the limitations of the research and their potential impact on the study conducted in this thesis.

2.2.1.4. Conclusion

To conclude, a literature review is an essential and integral part of research and scientific development. In our framework here, it is the first step undertaken. By conducting a literature

Review, one can look at current advancements and gaps and ensure that the research objectives can be clearly articulated and reflect the reality of construction site conditions. The literature review allowed us to conclude that a systematic improvement of several aspects of material, labour, and equipment usage on site is yet to be articulated.

2.2.2. Research Objectives

Based on the literature review, the research gaps were identified. Analyzing current research allowed us to develop research questions that would provide clarity regarding the study's goals.

- Investigate the most common patterns of shear masonry walls and derive their deltas from a lean perspective.
-

The first research objective is to investigate the existing types of walls and derive their deltas from a lean perspective. Investigating the different types of walls allows us to get all possible combinations that need to be studied. For this objective, construction site visits and observations were made. The author classified the walls according to the shape and complexity of the work involved in the wall patterns. The second step is to extract their deltas based on the on-site observation. To extract their deltas, a lean point of view was adopted. Activities relating to a specific wall pattern were analyzed, and the deltas in constructing such walls were inferred based on the construction process of the different patterns.

- Identify bottlenecks in masonry construction activities performed related to a typical horizontal shear masonry wall using Value Stream Mapping and Simulation Modelling.

The identification of the different bottlenecks for a typical shear wall was performed using two tools: Value Stream Mapping and Simulation Modelling. The techniques used in each will be detailed later in this Chapter.

- Develop a framework to reduce the waste related to construction lead time and compare productivity for proposed new construction systems.

The Framework developed is the artifact of the DSR methodology adopted in this study. The main goal is to reduce construction lead time by proposing new construction systems. The construction systems are evaluated against each other, and their impact is also tested when implemented together using Simulation Modelling.

2.3. Framework Development

The framework (or solution development) comprises four distinct steps: Data Collection, Value Stream Mapping, Simulation Modelling and Lean Interventions. It begins with collecting data concerning the process, the different types of wall construction and the different steps involved in a construction process. The second step consists of developing a value stream map to detect the bottlenecks in the system. It comes after studying the process based on previous data collection. The third step is to simulate the process in question using Simulation Modelling to check the system's long-term behaviour and infer the different problems for potential improvements. The last step is proposing lean improvements to remediate the problems and bottlenecks that were found using Value Stream Mapping and Simulation Modelling.

2.4. Data Collection

The data used in the study of improvement of construction site conditions can be done in a myriad of ways. In addition to construction site visits, this study's author used video recordings, interviews, time studies and motion studies. The video recordings and construction site visits were used to identify the duration of some of the activities (time studies) and analyze worker interaction and movement on site (motion studies) as well as equipment and material usage. Going on-site allows the understanding of the dynamics of construction projects. This research took the opportunity to visit construction sites better to understand the crucial steps in the construction process. Using video recordings allowed the researcher to accurately perform the time and motion studies of a construction process. They provide a detailed account of the different activities and interactions happening on-site. The data was collected for the 8”x8”x16” semi-solid CMU block when constructing a typical horizontal masonry wall.

The interviews performed (study ID: Pro00133067) aimed to gather quantitative data regarding the construction process and ask for historical data regarding the construction process. The interviews also provided the opportunity to validate the results obtained for the data collected and those obtained in the Value Stream Map and Simulation Modelling developed.

2.5. Value Stream Mapping

Following Data collection, a Value Stream Map is developed to identify the bottlenecks in the process. The Value Stream Map was created using the following steps:

I Defining the scope: The scope of work is first determined based on the study to be performed. In this study, the scope was inferred based on the observations made on the construction site. It is essential to note that the value stream map's scope must be comprehensive. However, the availability of data available also limits the scope of the value stream map being developed. The scope of the value stream map must include the most important construction steps of the construction process being studied. Moreover, the scope should be inclusive enough to understand what is happening on-site and capture the interaction between the different moving parts on site.

II Collect the Data: Use the data collected in the previous step to find each step's cycle time in the construction process studied. In the case- study presented by the author, the data was used for the five steps constituting the masonry construction process.

III Map the Current State: It is necessary to map the current state, including moving materials and equipment on site. Inventory and information flow are also included in this step. In our case, the value stream map was developed with the idea of value generation in mind and validated by a masonry construction industry practitioner.

IV Identify the bottlenecks: The identification of bottlenecks is done by looking at the activities that have the biggest cycle time. These activities would be considered problematic for the flow of construction on site.

2.6.Simulation Modelling

Following the development of the Value Stream Map, Simulation Modelling is done to get the behaviour of the system in the long run.

Six steps are undertaken:

I Defining the Objectives: The objective of the Simulation Model is to pinpoint the different areas of waste in the construction flow on-site. This objective helps us interpret the simulation model and build the model based on the current state value stream map developed beforehand.

II Assumptions: The assumptions made when creating the model. It is essential to define the assumptions on which the simulation model is based. In our case, the supply chain was not integrated into the developed model.

III Model Input: It is important to define the resources found on the construction site. The resources would consist of the different materials that are being used on-site to progress through the construction flow. Moreover, the duration of the activities must be included in the model. In the case of waiting times for a resource, putting conditional conditions is also crucial. All of the data that is fed into the model needs to be accurate to ensure the reliability of the simulation model.

IV Verification: A check for the model's inconsistencies and errors is required to ensure that the model accurately represents construction site conditions. Verification is done using desk, white, and black box checking.

V Validation: The Validation of the results is done using face validity, event validity, and internal validity. Face validity is done by asking for expert opinion (in our case, masonry construction industry practitioners) about the developed model for the construction process being studied. Event validity is done by comparing the model's behaviour with the expected behaviour of the construction system in real life. Internal validity is done to check the variability of the results of the simulation runs being performed.

VI Results and discussion: The model for the construction flow is studied, and three metrics are considered: Construction Lead Time, Daily Productivity Rate and Utilization Rate. The Construction Lead time was found by looking at the time it takes for one iteration of the process to be completed. In our case here, one CMU block passes through the entire construction flow of the simulation model. The daily productivity rate is calculated based on the number of work hours every day. It is calculated using the following formula shown in Equation 1:

Equation 1: Daily Productivity

$$Daily\ productivity = number\ of\ work\ hours * \frac{number\ of\ bricks}{duration\ of\ simulation}$$

Considering a fixed number of blocks, the simulation is run. Based on the total time it took to complete X rows of Y blocks, it is possible to get the time it takes to process one CMU block. Assuming a 7-hour workday, it is possible to get the daily productivity in blocks/day.

Station Utilization is a metric that is a metric that is given when running the simulation model. Knowing the mean station utilization rate (expressed as a percentage), it is possible to see what part of the process has the highest variability by calculating the coefficient of variation. The coefficient of variation is calculated using the following formula (shown in Equation 2):

Equation 2:Coefficient of Variation

$$Coefficient\ of\ variationf\ variation = \frac{standard\ deviation}{mean}$$

The coefficient of variation allows us to know where variability is the highest in a process and consequently look for ways to mitigate the variation in one of the processes identified as such.

2.7. Lean Interventions

Lean interventions are ways to reduce waste and variability in the construction process while simultaneously adding value. After identifying the sources of waste, it is possible to remediate. Liker (2004) introduces the "Toyota Way," which consists of 14 principles. This section details the application of these 14 principles in a construction context. The principles can be applied after pinpointing what is going wrong in a construction system based on the observations and deductions made using Value Stream Mapping and Simulation Modelling.

1. Long-term thinking: This principle emphasizes the importance of long-term planning when it comes to construction. It comes with the idea that durability and sustainability should be integrated into any construction process we seek to improve.

2. Continuous Flow: Continuous flow is achieved by streamlining a construction process, minimizing wait time, and reducing delays (such as idle time waiting for material, equipment, etc.). Continuous flow means standardizing the sequence of steps undertaken in a construction process from material delivery to demobilization.

3. Pull: Aligning the work schedule is crucial when adopting a pull system. By planning in advance, excess inventory of materials and resources is avoided. The reduction in the use of resources by proper pull planning leads to a decrease in the project's overall cost.

4. Level: Levelling the workload prevents uneven work, which leads to bottlenecks and constraints on the resources during the construction flow. Levelling the workload leads to increase productivity.

5. Standardized processes: Developing a standardized process to follow during construction ensures a decrease in variability, enhanced efficiency, and subsequent increase in productivity. By standardizing the work in a construction process, we ensure a reduction in the probability of rework and errors.

6. Design-Build in Quality: To get quality, it is essential to involve construction professionals

in the design phase of a project to address potential issues that may stem from a design (a wall shape, for example). Doing so reduces the probability of encountering rework later during construction, leading to increased costs and budget overruns.

7. Visual Control: Implementing visual control tools such as a Kanban Board (simple boards with the current state of tasks on site: Backlog, Doing, Review, Done) can help in case quick decision-making is required.

8. Technology to Support People and Processes: Introducing new technology, such as robots to create semi-autonomous construction systems, would enhance overall project performance and facilitate work on site by giving the robot tasks that may be considered strenuous to a construction worker.

9. Grow Leaders: Fostering a culture where the entire team is able to work effectively by training the supervisors to lead a team toward success. Adopting a "blame the process, not the person" culture enables changes to happen when a construction system or flow fails.

10. Develop People and Teams: Investing in training in using specialized tools for those involved in a construction process would facilitate work on-site with the acquisition of new skills. Moreover, training, and individual development lead to a culture of continuous improvement on-site.

11. Partner with Value Chain: It is important to collaborate with the different stakeholders on a construction site (suppliers, general contractors, subcontractors, etc.), where partnership and open communication are strong to foster a culture of project success.

12. Observe Deeply and Lean Iteratively: Learning from previous projects and methods that have been used in the past and are used currently allows us to analyze the successes and failures that have already happened and build upon them to refine and optimize construction site conditions.

13. Align Goals: Ensure the goals are aligned among all the stakeholders. It is also essential to define the success criteria for the construction project.

14. Bold Strategy. Large Leaps and Small Steps: New strategies and construction methods should be encouraged. Small improvements to day-to-day operations and steps undertaken in construction lead to efficiency and improvement of construction site conditions.

2.8. Scenarios Testing

Testing the different solutions is done by simulating them and comparing them to the traditional constriction process being studied using three metrics: Construction Lead Time, Daily Productivity Rate and Utilization Rate. When comparing, it is also essential to validate the results obtained and perform the validation of these results. Coming up with a conclusion would depend on which solution (or combination of solutions) would perform the best according to the metrics chosen and lean principles. Figure 2 shows the improvement framework (the artifact) of the Design science research applied in this study.

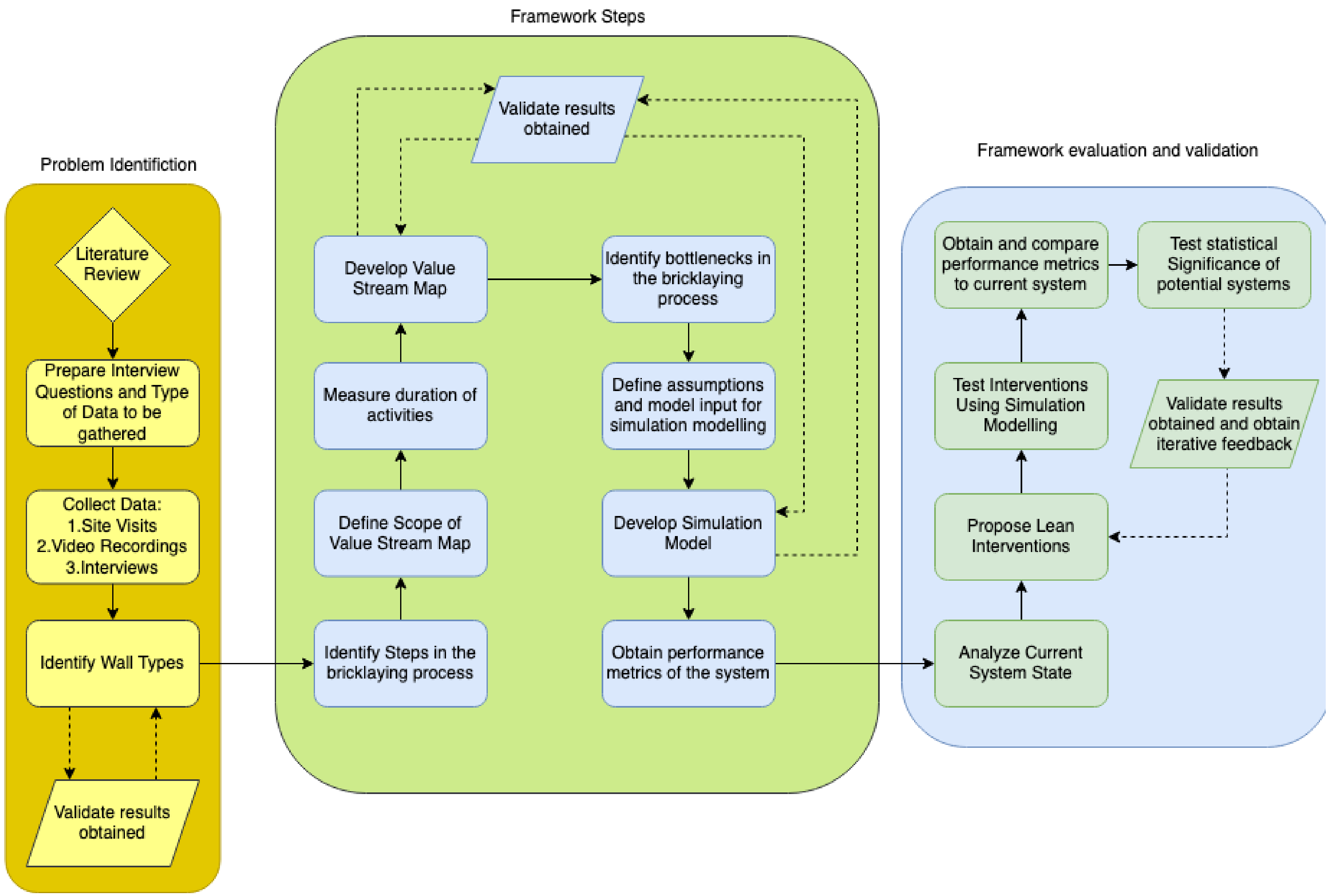

Figure 2: DSR Improvement Framework Steps

3. Literature Review

3.1. Introduction

The construction industry has undergone significant improvements throughout the years. However, construction sites still face several issues in terms of waste affecting productivity, costs, and scheduling, ultimately affecting the value offered to the customer. Lean Thinking was introduced in the last few decades to overcome these challenges. The study presented in this thesis focuses on production system design in a construction site setting. Hence, the inclusion and subsequent inclusion of lean tools, including Value Stream Mapping and Simulation Modelling, is essential to increase value and reduce variability on construction sites. It is, however, worth noting that none of the studies were made to improve construction site conditions from material, labour, and equipment perspectives together and using the tools and methodologies used in the analysis presented in this thesis. Scarce data (Melo et al., 2017; Abbasian-Hosseini et al., 2014) can be found in the current body of scholarly works, tackling construction site conditions improvement, and considering the flow on-site rather than mitigating the specific impact of a particular shortcoming.

3.2. Lean Construction

3.2.1. Lean Thinking

Lean Thinking is a philosophy that aims to decrease waste generation by consuming fewer resources (time, labour, inventory, etc.) while maximizing delivered value to the customer. It can be summarized as "Lean is doing more with less" (Womack & Jones, 1996). Hence, Lean is a systematic approach to problems of generating value on construction sites.

Three decades ago, Koskela, 1992 introduced Lean thinking to the construction industry to improve competitiveness and the state of the industry. Traditionally, waste activities were not included in construction models, which considered only value-added activities. Lean construction was proposed to include flow processes, taking into consideration waste as well as conversion activities. This paradigm shift applied to the construction industry was a turning point in construction management research, followed using workflow planning and the Last planer system (Ballard et al., 1993), the introduction of Poka-yoke and Kanban systems (Milberg & Tommelein, 2003; Arbulu et al., 2003), as well as the establishment of a framework of lean construction and production (Salem, 2006).

Womack and Jones, 2003 cited the following five lean principles:

1. Defining Value as per the ultimate customer views.
2. Identifying the entire value stream for each product and eliminating waste.
3. Making the remaining value-creating steps flow.
4. Designing and providing what the customer wants only when the customer wants it.
5. Pursuing perfection: Keep reducing effort, time, space, cost, and mistakes.

Lean, as a concept, was first applied to the Toyota manufacturing industry, which was oriented towards tailoring production based on customer needs (it has evolved over the years to become a cornerstone in all areas of construction management from production to workforce, materials, and technology, among others. Lean Thinking was applied to the construction industry around three decades ago (Fontanini et al., 2013). It was then experienced in several countries, like Brazil (Conte & Gransberg, 2001), that reported a success story in more than 20 construction companies adopting this philosophy.

The construction industry suffers from high rates of waste, reaching up to 57% (Bajjou et al., 2017). Therefore, the introduction of Lean to this field was crucial. Lean is currently described as the “excellence benchmark” in this sector, with a significant impact on the decrease of waste (Bajjou & Chafi, 2021). In a recent study, Hamzeh et al., 2021 described the triad needed to implement Lean management in the construction industry: Lean “Philosophy”, “Culture”, and “Technology”. The authors consider that Lean Philosophy involves waste and value, both reflecting production knowledge, while culture requires a mentality change among workers towards Lean Thinking.

The role of Technology using, for example, Value Stream Maps and recently Virtual Models, Last Planner System and Target Value Design as supporting methods of Lean implementation is essential (Hamzeh, 2021). Furthermore, Lean production can be considered as the guarantee of material quality and quantity, thus reducing waste to the minimum while keeping the flexibility to adapt to any production variability (Bajjou & Chafi, 2020; Mao & Zhang, 2008).

3.2.2. Construction Waste Concept and Lean

The concept of construction waste was believed to be directly and exclusively related to the debris resulting from construction activities, and it has always been present in construction sites at very high levels (Formoso et al., 2002). A few decades ago, it was defined as "the difference between the value of materials delivered and materials used in the work" (Pheng & Tan, 1998). However, with the application of Lean thinking, waste is defined as any inefficiency resulting from equipment use, material, labour, and cost (Koskela, 1992).

Several research studies identified the types of waste affecting the construction industry, aiming to implement lean thinking into the process. In 2005, Zhang et al. reported two case studies in housing construction, showing that an increase in productivity and better quality could be reached by resource waste control. The authors suggested including all factors such as labour, material, equipment, data, time, and workspace. Ballard et al. 2001 tackled the variability factor as an important source of waste in construction and the importance of flow production in reducing cycle time in home building. Reducing flow variability by addressing flow production was also considered by Bashford et al., 2003.

Sources of waste can be variable, including design (Al-Hajj & Hamani, 2011), material procurement and handling (Alwi et al., 2002; Poon et al., 2001) as well as operational challenges (Polat & Ballard, 2004; Formoso et al., 2002). Material, labour, and time represent major waste components in the construction industry. All these factors can variably impact construction flow, productivity, and value generation.

Physical construction waste is the waste that comes from any construction activity, such as excavating, building, renovating, or even demolishing (Kalild & Al-Zubaidy, 2018; Kofoworola & Gheewala, 2009; Tam & Tam, 2008; Shen, 2004). However, construction waste can also be non-physical such as cost overruns and delays. Costs overrun represents the difference between the initial estimated and actual costs upon construction project completion (Choudhury & Phatak, 2004). These are unexpected, incurred costs exceeding the initial budget (Shanmugapriya & Subramanian, 2013).

Time overruns or the extension of the planned completion date of a project (Kaming et al., 1997) can be defined as the difference between the actual and estimated completion time (Choudhury & Phatak, 2004; Chan, 2001). Delays in project completion dates (Al- Gahtani and Mohan 2007) can occur with the execution and performance of unnecessary work leading to decreased productivity and higher total project costs (Polat & Ballard, 2004).

In a study by Senaratne & Wijesiri conducted in 2008, ten types of waste were identified, mainly pertaining to material defects, followed by unnecessary labour and movements, design errors and timing delays. The root causes of flow waste were mainly related to delayed information, poor management control and planning, and hindering construction efficiency. All these causes were controllable. Moreover, the acceptability of lean construction principles was tested among workers and "company-wide" and was found to be acceptable and applicable.

Reducing waste using lean construction can also be accomplished by reducing material waste on construction sites. A survey of 226 individuals conducted by Agyekum et al. (2013) described the root causes of material waste on site and developed lean practices to decrease the waste generated. It was found that the leading causes of material waste on site tend to be related to material handling, procurement, storage, and procurement. The authors concluded that two of the most common types of waste occur in mortar/cement and blocks, two essential materials used on construction sites. Using lean principles with a philosophy of reusing, recycling, and reducing the use of materials leads to better project performance and value delivery for customers. Reducing waste in materials is critical due to their significant share in the cost overrun of a project. Indeed, up to 30% of a budget overrun is due to material waste (John & Itodo, 2013). Bajjou and Chafi (2021) identified seven types of waste: overproduction, unnecessary transportation, excess inventory, waiting, defects, overprocessing, and unused employee creativity. They concluded that these types of waste could be remediated using lean principles by reducing the share of Non-Value Adding activities in a construction process and optimizing flow on a construction site.

From a scheduling perspective, Walia and Suri (2017) detailed the effect of using the Last Planner System, a lean technique where all project participants contribute to the planning and scheduling of a construction project. It was found that the Percent Planned Complete (percentage of planned work completed at a certain given time) was significantly higher when using traditional scheduling and planning methods.

On another note, implementing lean thinking is not limited to waste reduction on construction sites but also touches on the different elements of a construction life cycle, such as procurement. Wilson and Roy (2009) considered that Lean procurement can improve production efficiency and leads to cost savings. Correlations between construction procurement and Lean principles were reported by Vilasini et al. (2011). Recently, Suresh and Nathan (2020) studied ten factors, including the cost of material and supplier selection, affecting lean procurement and subsequent construction project organization, among others. They showed that supplier selection played a major role in Lean procurement readiness.

In conclusion, the umbrella of Lean Construction covers multiple aspects nowadays, from management to workforce and, recently, technology. The new vision of Lean Construction 4.0 introduced by Hamzeh et al. (2021) embraces the new industrial revolution while incorporating digitalization and automation (Lasi, 2014). Pairing Information Technology and the human workforce seems very promising. The major challenges with this vision reside in the willingness of the industry to embrace this rapidly evolving relationship between Lean Construction 4.0 and the latest Information Technology.

3.3. Value Stream Mapping

Value Stream Mapping is a visual tool used in lean thinking to organize, analyze, and improve the construction flow of a certain process (Fernandez-Solis & Li, 2018). It was first introduced by the Toyota industry around two decades ago (Liker, 2004; Baby et al., 2018), then it was applied afterwards to the construction industry (Pasqualini & Zawislak, 2005).

A longitudinal study of the efficacy of lean learning experienced through a simulated working environment (SWE). *International Journal of Productivity and Performance Management*, *66*(5), 651-661.

Value Stream Mapping consists of a series of graphic presentations of the value flow, starting from the customer's order up to the delivery of the product, aiming to identify waste in the analyzed process (Rother & Shook, 2003). With Value Stream Mapping, all activities in a process are categorized as Value- and Non-Value-Adding (Rohac & Januska, 2015). It allows the development of lean thinking and improvement strategies based on a deeper analysis of the workflow with the goal of delivering value to the customer. (Martin and Osterling, 2013).

3.3.1. Value Stream Mapping Tools

The Value Stream Mapping tools described by Hines and Rich in 1997 included seven steps contributing to waste elimination:

1. Mapping of the process activity.
2. Creating a matrix of the supply chain responsiveness, identifying limiting activities in the process.
3. Tracking the production process with product variety funnelling.
4. Quality filter mapping.
5. Forrester effect mapping by analyzing the disturbance on the supply chain of reorder activity and identifying a decision support system.
6. Decision point analysis identifying "the point in the supply chain where actual demand-pull informs forecast-driven push."
7. Overall structure mapping, identifying the gaps to be improved within the whole picture of the supply chain.

3.3.2. Value Stream Mapping Application

The application of Value Stream Mapping in the Architecture, Engineering and Construction (AEC) industry was studied in various settings, like ceramic (Pasqualini & Zawislak, 2005) and concrete block masonry (Al-Sudairi, 2007). However, Value Stream Mapping application in construction is still limited to specific areas (Fernandez-Solis & Li, 2018). Some research studies reported Value Stream Mapping application in the supply chain (Fontanini & Picchi, 2004; Arbulu & Tommelein, 2002) or project delivery (Mastroianni & Abdelhamid, 2003), all related to macro-level processes.

Nevertheless, some limiting factors were identified in Value Stream Mapping application in construction, as compared to the manufacturing industry:

- The difficulty of repeating the production process since each construction project is distinct from the others.
- The difference between manufacturing and construction is in terms of using some Value Stream Mapping tools, such as Takt time and inventory, as studied by Yi et al., 2009.
- The non-availability of process data in many construction companies.

Hence, the need to use a modified Value Stream Mapping was necessary. In fact, very few studies addressed the application of Value Stream Mapping as a technique in the masonry industry. One of the Value Stream Mapping applications to structural elements such as walls and columns was performed by Pasqualini and Zawislak, 2005. These elements were defined and analyzed as a "product family" in the construction process. The authors analyzed a masonry stage, calculating the Takt time considering the effective worked time and the amount of area worked to delineate the production rhythm based on the contract schedule.

Yu et al., 2009 applied a modified Value Stream Mapping to housing construction, focusing on the discrepancy between predetermined schedules and possible unpredictable delays, which reflect the differences between the manufacturing and construction industries. The study proposed a practical modified approach to Value Stream Mapping application in construction.

Fontanini et al. 2013 presented the concrete slab value stream mapping of a residential building in Brazil in a case study. They found that Lean Thinking was “informally” applied, as evidenced by the absence of some waste in the studied construction case. In addition, Rosenbaum et al., in 2014, a case study of the Value Stream Mapping application to assess environmental and production waste in a construction stage, highlighted the importance of this tool in reducing waste and improving the sustainability of construction projects.

Melo et al., in 2017, mapped the current state of masonry construction using construction site observations, interviews, and historical data. The Non-Value-Adding time was found to be 32.45% of the total time, explained mainly by unloading materials and transportation to the construction site using cranes. Based on the developed current state Value Stream Mapping and its analysis, the authors suggested that Lean thinking could be implemented in a future state Value Stream Mapping. By applying different lean tools such as Kanban, Heijunka boxes and Kaizen bursts, the total Non-Value-Adding time was reduced by 60.55% compared to the current state Value Stream Mapping. The lead time was also reduced, which would lead to better productivity. The future Value Stream Mapping goal would be the minimization of uncertainty in the construction of rows composed of masonry blocks.

In a study by El Sakka et al. (2016), a detailed analysis of a company manufacturing process using Value Stream Mapping was achieved by visualization of determined processes, including ordering, manufacturing, and delivering, to propose Lean concepts application. Furthermore, precast concrete building construction processes and differences in flow between developed and developing countries were recently studied by Xiaosheng et al. (2020). The precast of the processes from the initial design to the construction completion was mapped, combining the material flow and information flow of these activities. Using Value Stream Mapping for precast construction opens the way for a better application of Lean concepts and tools (Xiaosheng et al., 2020).

In a structured review by Fernandez-Solis (2018), the authors concluded that Value Stream Mapping could be applied in the construction industry in three categories:

1. The construction process to identify waste in production and environment while using modified Value Stream Mapping (Yu et al., 2009) for waste during a stage of the

process.

2. Construction macro-process to add value and reduce waste.
3. Construction support process to improve the supply chain and the production process

In conclusion, Value Stream Mapping is a crucial tool successfully applied to the manufacturing industry in the last two decades. Given the differences between the manufacturing and construction sectors, some modifications to Value Stream Mapping techniques were proposed by researchers in the construction field. Value Stream Mapping help identify the bottlenecks on site and remediate the root problems, which would allow an increase in value delivered on the construction site with improved construction site conditions. Future directions of Lean construction using real-time value stream mapping would be heading towards adopting Lean Construction 4.0 (Hamzeh et al., 2021) to this ever-growing field.

3.4. Construction Simulation Modelling

Over the last five decades, Construction Simulation research has evolved with the advances in information technology, computer programming languages and power (Abdelmejid et al., 2023; AbouRizk, 2010). Simulation Modelling represents an integral part of Lean Construction (Halpin & Kueckmann, 2002). It is defined as the "science of developing and experimenting with construction systems using computer-based models, aiming to understand their behavior" (AbouRizk, 2010). This tool allows one to mimic an operating system, analyze it, and experiment with its steps (Robinson & Stewart, 2014). Therefore, it can be used in production planning and construction systems control (Altaf et al., 2018).

Simulation Modelling is the most useful tool to assess the effects of lean application on a construction project before its physical execution (Van der Merwe, 2017; Lu et al., 2011; Wang et al., 2009). Several studies reported the superiority of using this approach instead of mathematical and experimental modelling, mainly owing to its easy use and accuracy (Nikakhtar et al., 2015; Abbasian -Hosseini, 2014; Hassan & Gruber, 2008; Al-Sudairi, 2007). Other studies considered Simulation a powerful tool to assess the applicability of Lean thinking in construction (Abbasian-Hosseini, 2014; Hosseini et al., 2012; Agha et al., 2010; Mao & Zhang, 2008; Bamana, 2018).

Furthermore, it was shown to improve construction operational gains in areas of concrete and building walls, as well (Halpin & Kueckmann, 2002).

Abbasian-Hosseini et al. (2014) studied the effect of applying Lean to a masonry construction process using Simulation. The authors showed a significant increase in productivity by 43% and operational efficiency by 27%; on the other hand, cycle time was decreased by 41%. The crucial role of Simulation Modelling was further highlighted by Abdelmegid et al. 2020 in the era of rapid technology advances and its applications in the AEC industry.

In 2008, Mao and Zhang designed a construction framework combining simulation and lean principles techniques. Since, Construction projects are considered complex systems that include various activities and flows (Abdelmegid et al., 2023), advanced Simulation Modelling technologies are required (Martinez, 2010). Nowadays, simulation is being coupled with other technologies like data-driven modelling (Akhavian & Behzadan, 2018), Building Information Modelling (Lu & Olofsson, 2014), Virtual and Augmented Reality (Kamat et al., 2011), and hybrid modelling (Peña-Mora et al., 2008).

3.4.1. Stages of Simulation Modelling

Four stages of Simulation Modelling are usually described (Abdelmegid et al., 2023) for each construction project:

1. Conceptual Modelling: Define the problem, objectives, and content.
2. Model Coding: Construct a computer model.
3. Model Experimentation: Test the effect of the proposed model on the system performance using what-if scenarios.
4. Model implementation: Use the designed model to improve or create a new system.

3.4.2. Graphical Modelling

The use of graphical methods in Simulation Modelling became very popular with the advances in computer science technology (AbouRizk, 2010). Several simulation software was adopted by researchers in Lean Construction and Simulation, such as CYCLONE (Alkoc & Erbatur, 1998), SIMPHONY.NET (Wang et al., 2009), WITNESS (Nikakhtar et al., 2011), SIMIO (Bamana, 2018) and ARENA (Bajjou & Chafi, 2020).

Simphony .NET is a modelling software developed at the University of Alberta, Edmonton, Canada, for real-time simulation (Ekyalimpa et al., 2012; AbouRizk et al., 1998). It has been used by several researchers in construction (Moghani et al., 2011; Farrar et al., 2004; Fernando et al., 2003; AbouRizk, 2010), as it can model various work steps, modify the production process, and run simulations as much as needed (Afifi M. et al., 2016).

3.4.3. Simulation Modelling

Simulation Modelling is a technique used for "quantitative analysis of operations occurring in a constructed facility" (Martinez, 2010).

The application of Simulation Modelling in construction requires several steps, as detailed by Martinez (2010):

1. Assessment and definition of the model.
2. Data collection and use of basic probabilistic assumptions such as independence and identical distribution, fitting distributions, and testing for goodness of fit.
3. Model and data verification.
4. Validation of the model with subjects familiar with the real system, like experts, stakeholders, or decision-makers
5. Analysis of simulation output.
6. Decision making.

In conclusion, despite being used for a long time in Construction Engineering, stakeholders and practitioners still do not fully endorse Simulation Modelling as a decision-support tool (Abdelmegid et al., 2020; Leite et al., 2016). The underlying reasons for this reluctance could be related to the extensive time and cost incurred with this Lean tool. Nevertheless, the role of simulation remains at the heart of the automated Lean Construction revolutionary vision.

4. Investigating Masonry Wall Patterns

There are many types of masonry wall types. During the construction site visits, many visible configurations of the walls being built using CMUs were found. This chapter details the different configurations of masonry walls and consequently derives their deltas based on the on-site observations from a lean construction perspective. While many types of shear masonry walls exist, this study will focus on the typical horizontal shear wall made of 8”x8”x16” CMU blocks as per CSA A165.

4.1. Typical Horizontal Shear Walls

The typical horizontal shear wall is the most common type of wall used when building using CMUs on construction sites. Figure 3 shows the shape of a typical horizontal shear wall.

Figure 3: Typical Horizontal Shear Wall

Pros: This type of wall provides structural support to the building being constructed. The process is considered less time-consuming since the CMUs are put in a horizontal arrangement in the shape of a continuous line. Moreover, this type of wall configuration can also be used for non-load-bearing walls, which makes them a versatile choice.

Deltas: While this type of wall configuration is the easiest to construct, proper alignment is necessary when building this wall to avoid structural instability. From a labour perspective, repetitive motion leads to a decrease in motivation. From a material perspective, constantly refilling the mortar and CMU blocks stations is necessary. From an equipment perspective, the continuous use of forklifts makes it a safety hazard due to the constant movement of the forklift on site, which may injure someone. Hence, proper construction site layout planning is required when building the wall.

In conclusion, these walls are a foundational element due to their simple shape and versatility of usage.

4.2. L-shaped Walls

This shape is commonly found when building the corner of a structure. Figure 4 shows the shape of a typical L-Shaped Wall.

Figure 4: L-Shaped Wall

Pros: Due to their shape, they provide the stability needed for the junction between two walls. They also offer improved overall integrity from a structural perspective due to the smooth transition between the two intersecting walls forming the L-shape. Its use of stretcher and header courses makes it a relatively more straightforward shape to build.

Deltas: Alignment is also a concern in this shape. However, unlike the typical horizontal shear wall, additional mortar is required, as well as additional corner blocks. These additions increase the amount of resources needed is seen as a delta since additional work is required, and construction lead time would increase when building an L-shaped wall.

4.3. T-Shaped Walls

This shape is commonly found when support for heavy vertical loads is needed. Figure 5 shows the shape of a typical T-Shaped Wall.

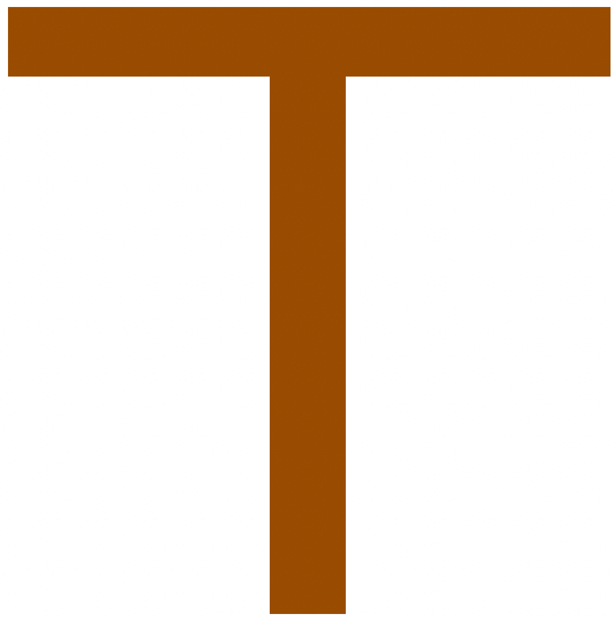

Figure 5: T-Shaped Wall.

Pros: Due to their shape, they offer better lateral stability compared to the typical shear wall. Moreover, they efficiently use the space available when building on a construction site due to their "compactness" compared to other wall types. Another advantage of this type of wall is the added strength that may result from the shape configuration. This added strength may prove advantageous in the case of multi-storey buildings.

Deltas: Additional planning may be required when dealing with this type of wall due to the added layer of complexity this shape provides. Furthermore, the horizontal component requires additional use of the material for this shape. This additional use of material can lead to higher costs. Another delta is the reduction of useable space in a building due to the wall itself. If a T-shaped wall proves to be thick, the interior layout of the building being constructed may prove to be less flexible. Moreover, additional formwork and bracing may be needed for this horizontal cross-section.

4.4. U-Shaped Walls

This shape is commonly found where aesthetics is a crucial element of the finished construction project. Figure 6 shows the shape of a typical U-Shaped Wall.

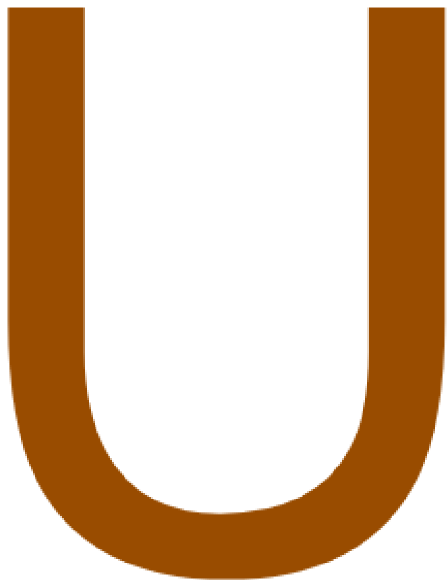

Figure 6: U-shaped Wall.

Pros: This type of all is aesthetically pleasing due to its curved shape. It also utilizes the space available on site when space is limited.

Deltas: Additional planning may be required when dealing with this type of wall due to the added layer of complexity this shape provides. Furthermore, the curved component requires additional use of the material for this shape. This additional use of material can lead to higher costs. Another delta is the labour-intensive and time-intensive nature of building such a shape due to the curvature itself.

5. Data Collection and Case Study

5.1. Case Study

The case- study is a school gymnasium constructed in the Edmonton area of Western Canada. It is being built by a leading masonry contractor in Alberta that specializes in commercial, residential and restoration work involving masonry. The school gymnasium studied presents multiple wall shape configurations, namely L-shaped walls at corners, typical horizontal shear walls and presents openings such as windows and doors that necessitate the use of a lintel. The contractor deals with other contractors and construction companies to build masonry walls made of CMUs. The masonry crew on site is made of labourers and helpers erecting the masonry walls that need to be built. The masonry crew has a primordial role on site since any event that delays the team would delay wall construction and successful assembly using the CMUs. This chapter focuses on the details of masonry construction and the origin of the data used in this thesis. In our case study here, the process studied is limited to 8”x8”x16” CMU blocks are defined by CSA A165 as semi-solid blocks of normal weight (28 lbs). The masonry construction process studied on these semi-solid blocks is done for typical horizontal shear walls only with no protrusions, changes in height, over openings, at wall intersections, at wall corners or pilasters. The data was collected by observing different masons with different levels of experience at different parts of the wall being built to have the most representative data set possible. The process also assumes no rework on any section of a typical masonry shear wall.

The current flow of information on the construction site is shown below in Figure 7. The steps represented are the steps necessary to build CMUs walls successfully. This thesis focuses on the masonry construction process. All prior and subsequent steps are not a part of this study.

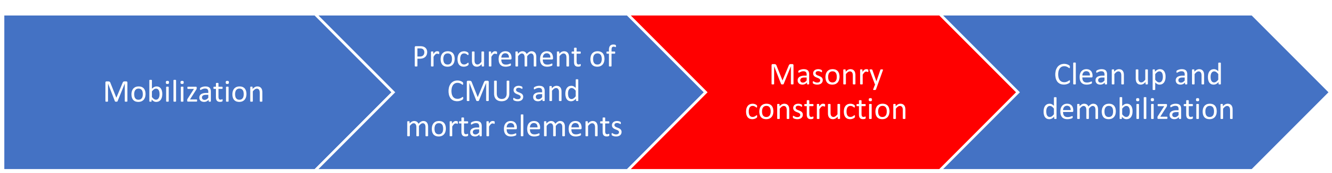

Figure 7: Information Flow on Construction Site

The first step in constructing a masonry wall is mobilizing labour, material, and equipment on the construction site. Mobilization generally involves preparing the construction site for masonry wall erection, such as placing a hydro platform for masonry construction on altitudes. After mobilization, the procurement of CMUs from the inventory and the mixing of water, sand, and cement to make mortar at a mortar mixing station. The Material Requirement Planning team calculates the quantities needed. The water, cement and sand are all dropped off at the mortar mixing station, while the blocks are unloaded simultaneously in the CMUs stocking area. The number of trucks supplying all the raw materials will vary from day to day due, depending on need. The trucks that unload the sand, water, cement, and CMUs will do so in an area of the site where space is available; there is no fixed space on the construction site where all the materials will be stockpiled. It should also be noted that unloading does not affect the masonry construction process itself, and both operations can happen simultaneously.

The crucial part of the process is masonry construction which is studied in this thesis. In this step, the actual construction of the wall is done. Once the wall is built, cleaning up all the excess waste material and demobilization is done. This step is done last after the completion of all masonry walls that are to be built. These steps are standardized when building on the construction site, as masonry wall construction involves repeating these steps independently of the wall or type of construction being done. As masonry construction constitutes the most important part of the workflow on the construction site, subsequent data collection is done for this workflow.

5.2. Process Description

Figure 8 shows the steps needed in the masonry construction steps of the workflow. Before the steps shown in Figure 8, a thread is placed along the row to be built to ensure the alignment of the blocks to be laid. Simultaneously, the mixed mortar leaves the mortar station in a mud tub via a forklift. The mortar in the tub is divided into different mud boards for the workers to use. This study focuses on 8”x8”x16" semi-solid blocks used to construct typical horizontal shear walls.

A small quantity of mortar is taken and spread on the location of the CMU block that is to be placed. The CMU block is then taken and laid on the mortar. The final steps in the masonry construction process involved knocking and levelling the CMU block before checking the alignment of the CMU block with the thread to ensure horizontality, as well as removing any excess mortar that is the result of knocking and levelling the CMU block. Finally, the jointing and finishing of the wall is done for all the blocks in the wall. The exact process is repeated for all subsequent blocks.

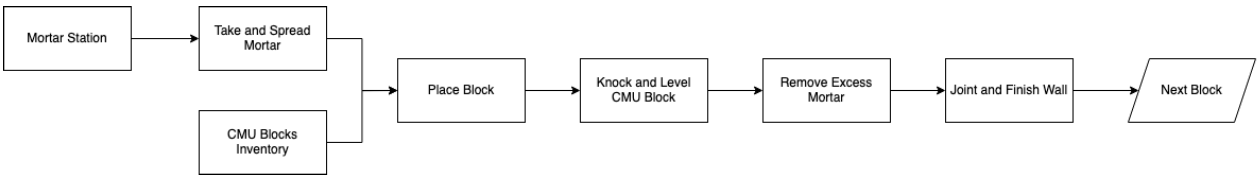

Figure 8: Masonry Construction Process

Figure 9: Wall Being Built.

Figure 9 shows a wall being built. In this case, a CMU block has already been placed, and the mortar for the following CMU block has been spread. The mason is getting a CMU block from the inventory (CMU blocks station) to put in and continue wall construction. Figure 10 shows a section of a wall being built. Here, we have three masons and two helpers at an altitude laying the blocks.

Figure 10: View of Wall Section Being Built.

Figure 11 shows the blocks and mortar stations at an altitude. These stations are refilled when needed with new material when the quantities are exhausted.

Figure 11: Mortar and CMU blocks Stations

5.3. Data Sourcing

5.3.1. Video Recordings

The duration of each activity in the masonry construction process was observed on-site and recorded for each of the activities of the masonry construction process. For data collection, a GoPro was set up on-site to record the labourers performing the different masonry construction activities on the construction site. The labourers performing the masonry construction activities can do simultaneously and do not affect one another as they work independently on multiple parts of a wall when masonry construction. When one labourer is performing one of the masonry construction activities, another labourer may be completing another task within the masonry construction process without the hindrance of another worker. The sequence of work in the masonry construction process is appropriately defined, and the exact steps are repeated for each subsequent CMU block used for wall construction. A wall at an altitude was chosen to be videotaped to extract the relevant data for the masonry construction process.

The videos were used to confirm the steps in the masonry construction workflow and identify the durations of each activity. The video recording also helped identify the value-adding and non-value-adding activities for subsequent process improvement. The presence of GoPro on the construction site did not affect the labourers' performance during masonry construction. Having gathered extensive recording data, the duration of each task was measured, and 31 data points were taken for both Value-Adding and Non-Value-Adding activities in the masonry construction process. Taking 31 data points ensured the obtention of normal distribution for all activities' duration based on the Central Limit Theorem (CLT).

5.3.2. Time Study

Based on the recordings obtained, it was possible to extract the duration of each activity using time studies. The goal of the time study that was done on the obtained video recording was to identify the duration of the masonry construction processes as well as make sure that non-productive time (such as being idle) is not taken into consideration when measuring the duration of all the activities of the masonry construction process as these times do not actively contribute to the process if present or absent. The time and motion studies aim to get accurate results concerning the masonry construction process regarding the waste generated within. The results obtained are summarized in Table 1. It is worth noting that the time study involved multiple masons with different skills and of different ages to get an as accurate representative data set as possible of masonry construction practices. It should also be highlighted that the time study was only done for straight horizontal shear masonry walls only.

CMU block Number	Take and Spread Mortar	Place CMU block	Knock and Level CMU block	Remove Excess Mortar
1	10	6	4	13
2	8	11	10	5
3	8	10	9	5
4	10	8	7	8
5	15	6	10	5
6	12	8	7	10
7	6	19	6	7
8	7	6	5	6
9	8	9	13	9
10	21	10	8	6
11	10	3	11	8
12	11	9	12	8
13	12	11	16	10
14	13	5	11	20
15	10	12	12	7
16	15	11	11	9
17	12	6	16	5
18	9	6	15	12
19	11	7	8	7
20	7	10	9	4
21	8	13	9	5
22	8	11	7	4
23	8	6	5	3
24	7	6	12	2
25	5	6	7	4
26	5	6	6	7
27	4	12	11	5
28	5	6	8	4
29	16	10	8	3
30	20	23	9	6
31	6	6	9	5

Table 1:Masonry Construction Process Time Study (in seconds)

5.3.3. Motion Study

Motion Studies were conducted to break down further the steps undertaken in the masonry construction process and identify the problematic activities. The motion study allows us to map what sub-steps form our main steps and to make sure to replace those steps with value-adding steps in the proposed new systems. The motion study was performed by observing the masons while performing the work and identifying the construction patterns.

Table 2 shows the different motions done at different steps of the masonry construction process:

Step	Actions taken
Take Mortar	-Lift Trowel -Take Mortar -Place Mortar on surface -Put Trowel Away
Place CMU block	-Lift CMU block -Move to area of placement -Place CMU block
Knock and Level	-Knock the CMU block relative to the thread -Align with the thread
Remove excess mortar	-Take Trowel -Remove Mortar -Take away the excess mortar

Table 2:Motions Undertaken in the Main Masonry Construction Steps

5.3.4. Interviews

Interviews were performed with the site superintendent to confirm the time of jointing and finishing as it does not relate to a single CMU block but rather the entirety of the wall being built. The average value was found to be 40 blocks per hour. For this exercise, this duration was expressed per block in subsequent data usage.

5.4. Conclusion

This chapter focuses on the overall masonry construction process and how the data was collected and obtained. This chapter also explains the overall way information flows on construction sites. Data was collected and gathered using video recordings and time studies to accurately identify the patterns and steps previously identified in the masonry construction process. Data gathered will be used in subsequent chapters to understand how current construction patterns are hindered by waste (Non-Value-Adding activities) and uncover current productivity problems in terms of lean theory. Chapter 4 presents Simulation Modelling of the current masonry construction process.

6. Value Stream Mapping

6.1. Introduction

A Value Stream Map shows all the steps on the construction site to erect a wall made of CMUs. The actions taken on site can be divided into three parts: Value Adding, Non-Value-Adding but needed (necessary waste) and Non-Value-Adding activities. To be considered a Value Adding activity, the action that is being taken should. The erection of walls using CMUs includes many resources, namely CMU blocks and mortar. The process starts upstream with a request for materials by Production Control and ends downstream with the assembly of a wall configuration. The different processes making up the Value Stream Map will have input and output after the process. The mortar is composed of cement, sand, and water. All these components are brought to the site by their respective suppliers. The Value Stream Mapping developed is done for the scope of the case study mentioned in the previous chapter.

The goal of developing the Value Stream Mapping is to identify the bottlenecks in the masonry construction process, creating a comprehensive step-by-step state of the current practices from the unloading of the CMUs on-site to the completion of the laying of one CMU block. The Value Stream Mapping also contains the number of workers involved in each step and an inventory of mortar and CMUs on site. A workday is assumed to be of 8 hours. The goal of the Value Stream Mapping is to be able to comprehend how the different elements on the construction site interact together, as well as share the total duration of each activity that is happening on site. This method allows everyone to get familiar with the many moving elements on site that interact for a better understanding of the whole process. Creating the Value Stream Mapping enables everyone on site to be vocal about the steps being undertaken and hence be part of the problem identification and the solution process. Value Stream Mapping as a tool enables one to view the whole process but also as a sum of parts and be able to view each part individually. Chapter 4 of this study presents the steps undertaken to develop the Value Stream Mapping, establishes the current state of masonry construction, concludes the bottlenecks in the process, and serves as a basis for the simulation modelling that will be performed later in the study.

The current Value Stream Map of the masonry construction process starts with requesting the different materials needed for mortar preparation and CMUs from their respective suppliers. Next, the Material Requirement Planning team calculates the quantities required. Finally, the water, cement and sand are all dropped off at the mortar mixing station while the blocks are unloaded simultaneously in the CMUs stocking area. The number of trucks supplying all the raw materials will vary daily depending on need. The trucks that unload the sand, water, cement, and CMUs will do so in an area of the site where space is available; there is no fixed space on the construction site where all the materials will be stockpiled. (Need unloading time for CMUs and mortar and mortar mixing time). It should also be noted that unloading does not affect the masonry construction process, and both operations can happen simultaneously.

Following the unloading of all the material needed on site, two scenarios are possible: the first for the lower-level rows when masonry construction and the second scenario for masonry construction rows at an altitude which requires the use of a hydro platform for the workers to stand on as well as a crane when need be.

6.1.1. Scenario 1:

The block is first placed after placing a thread along the row to be built to ensure alignment of the blocks to be laid. Simultaneously, mixed mortar leaves the mortar station in a mud tub via a forklift. The mortar in the tub is divided into different mud boards for the workers to use. Next, a small quantity of mortar is taken and spread on the location of the CMU block that is to be placed. The CMU block is then taken and laid on the mortar. The final steps in the masonry construction process involved knocking and levelling the CMU block before checking the alignment of the CMU block with the thread to ensure horizontality. The exact process is repeated for all subsequent blocks.

6.1.2. Scenario 2:

Workers need to be on a hydro platform for masonry construction at an altitude. Next, the mortar and the blocks are lifted to the appropriate altitude where the masonry construction operation occurs. All subsequent steps remain the same as in scenario 1. The lifting using the crane will depend on the location of the CMU block station on site and is variable, as previously mentioned. It should also be noted that the lifting of blocks to the elevated workstation happens simultaneously while laying the blocks on site. (Add time for crane to transport based on video).

The main objective of the Value Stream Mapping is to analyze the flow of material and information on the construction site. As previously mentioned, information flow on the construction site comprises four main steps: mobilization, procurement of materials, masonry construction, and clean-up and demobilization. Therefore, the main objective of the mapping is to identify the bottlenecks and the sources of waste in the system. Table 3 below defines the principal terms used in the legend of the Value Stream Map. One Value Stream Map is developed for both scenarios.

Terms in Legend	Definition
C/T	The time it needs for a CMU block to pass through a certain station
Shift Duration	Time available during one shift
CLT	The time a CMU block needs to move through the stream

Table 3:Terms Used in Value Stream Map

In the Value Stream Mapping created it is essential to note that the Value Stream Mapping includes the items relevant to this study and elements necessary to understand the flow of information and material on the construction site. The developed value stream map's objective is to understand the system's behaviour by giving a holistic view of the system.

Hence, assumptions were considered when developing the value stream map:

- Not all steps shown in the value stream map have a cycle time.
- The material suppliers of sand, cement, mortar, and CMUs are outside the scope of the map.

6.2. Value Stream Map

The Value Stream Map presented in this chapter is only related to the masonry construction process itself, from the moment blocks and cement are used to finishing the wall and grouting.

The value stream developed was made using data from constructing a school gymnasium. The procurement of materials for the masonry construction process was first brought into consideration. Still, since many variables outside the scope of the study control the procurement process, this process was excluded from the study. As a result, there is no inventory between the different steps of the process since every CMU block moves from one stage to the other before a new CMU block or mortar is introduced from the inventory (CMU blocks and mortar stations stationed across the wall being built).

The Value Stream Map was created after multiple site visits were conducted. The value stream map was revised multiple times as the steps taken in the masonry construction process became more apparent, and the average time for certain operations was taken into consideration based on the superintendent's feedback. The cycle times for the steps were taken to be the average time for each step.

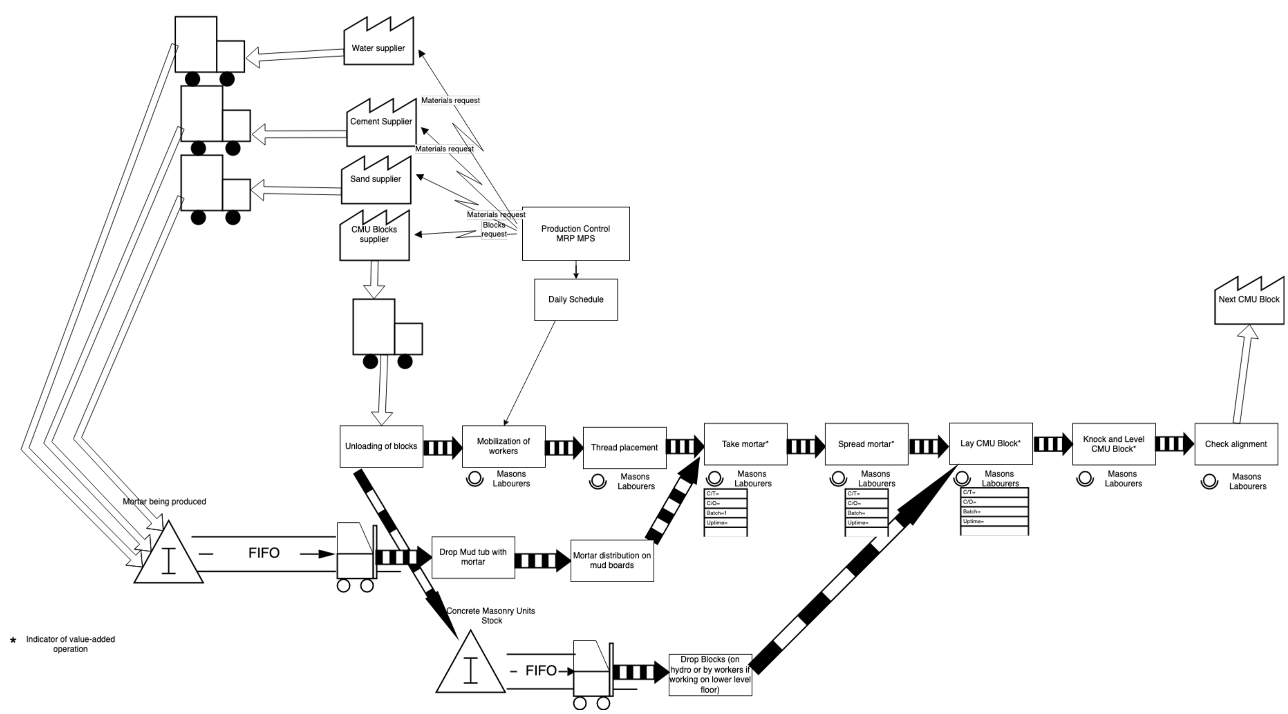

Figure 12:Value Stream Map-Construction Site

The Value Stream Map shown in Figure 12 was made on the construction site. Many steps, including the supply of material, were first included, and then not taken into consideration later due to the myriad of factors that may influence the supply of material outside the scope of the value stream map. There is no waiting time between the steps as they are taken concurrently.

The Value Stream Map above was further refined to include only the activities of interest in the study and make sure that the Value Stream Map accurately represents the steps studied in the masonry construction process. Figure 13 shows the current simplified state Value Stream Map. It symbolizes the construction flow of the process being studied.

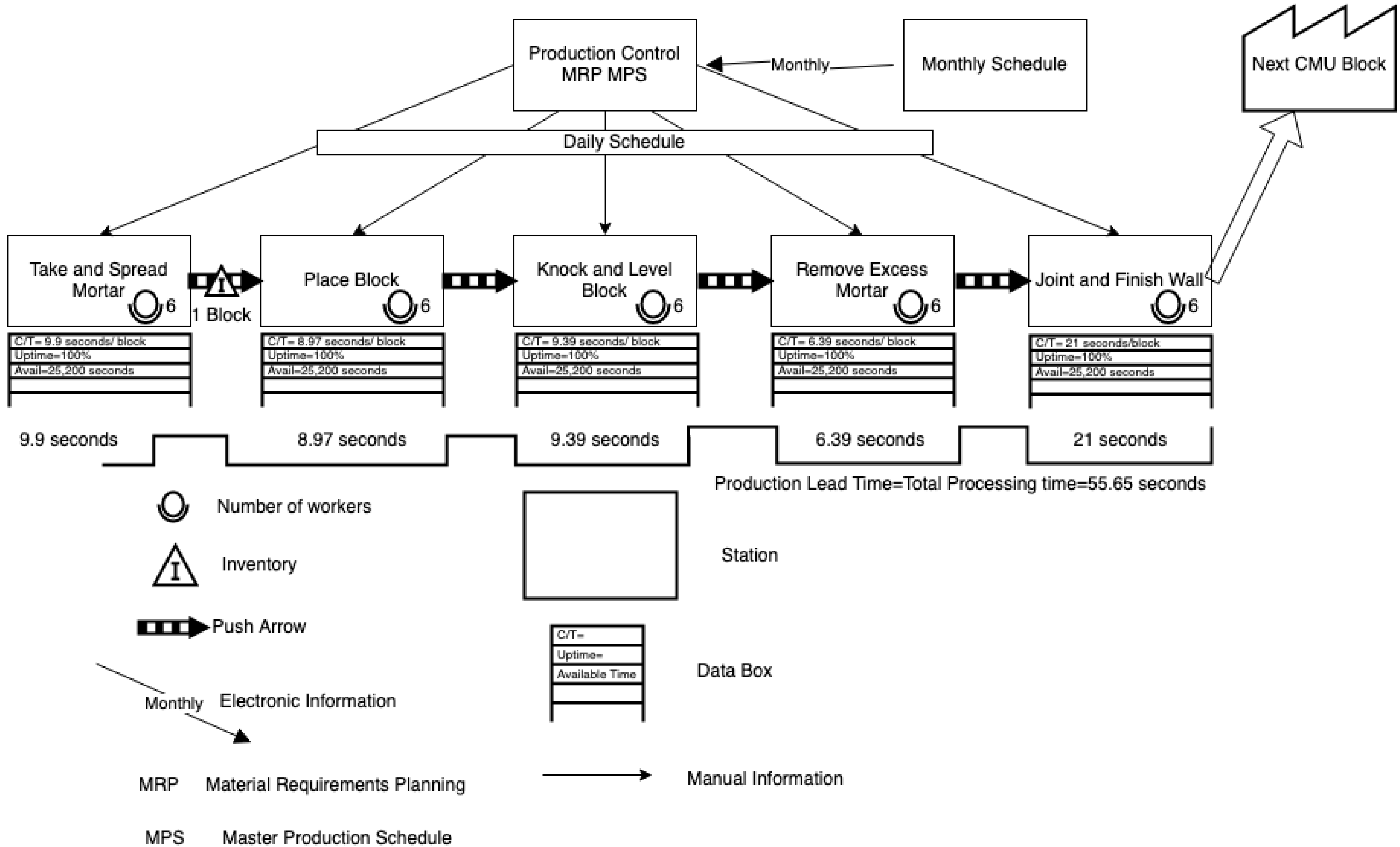

Figure 13: Masonry Construction Value Stream Map

6.3. Validation

The Value Stream Map was validated after development by the superintendent of the construction site, where the data collection and subsequent steps taken were deduced. The steps in the Value Stream Map represent actual steps taken on a construction site for masonry construction. Furthermore, the superintendent confirmed the duration of the different activities and the number of personnel found in the Value Stream Map to reflect the reality on the ground. Moreover, the superintendent validated the logic of the steps deduced in the Value Stream Map. The Map allows us to look closely at the different interacting parts on a construction site and understand the masonry construction process for further analysis.

6.4. Conclusion

The development of the Value Stream Map enables us to get a picture of the process to understand the different steps undertaken to complete a wall made of CMUs. The map helped us identify the deficiencies in the masonry construction process. The Value Stream Map permitted us to come up with the following conclusions:

1. The materials stations are affected by the suppliers and are considered outside the scope of this study.
2. A significant amount of time is spent handling the mortar, from taking, placing, and removing the excess mortar.
3. Further study using simulation modelling is done to see the current masonry construction productivity on site.

The Value Stream Map is used as a starting point for Simulation Modelling. The Simulation Modelling goal is to study and analyze the masonry construction process (base case) and come up with productivity and current construction site conditions. Simulation Modelling is also used for testing the lean interventions proposed to improve construction site conditions.

7. Simulation Modelling

7.1. Introduction

Having collected data for the different masonry construction operations, Simulation Modelling is used to get the duration of each operation and their share in the total lead time per CMU block laid-in wall erection. Using Symphony.NET software, distribution fitting was performed for the different activities of the masonry construction process. Simulation Modelling is used since it allows the prediction of the current masonry construction process behaviour in the long term as well as the identification of the share of Non-Value-Adding activities duration in the total lead time. It is possible to model the different steps using continuous distributions using the time study performed. The distribution fitting was performed on the data gathered, and the most appropriate continuous distribution function was chosen based on the goodness-of-fit tests Chi-squared and Kolmogorov-Smirnov (K-S). The distributions represent how each activity's duration is distributed and are used in subsequently developed simulation models. Simulation Modelling also permits the testing and obtention of results based on the impact of potential lean solution applications in the masonry construction process. Simulation Modelling will enable the discernment of the best lean applications on construction sites to maximize value and reduce waste.

In this chapter, Simulation Modelling will allow us to come up with conclusions concerning the current state of masonry construction on construction sites and explore the possible lean improvements possible based on the results obtained. This chapter details the methodology used to develop the simulation model, its verification and validation. Moreover, the model's results are explained and discussed.

7.2. Objectives

The first step in Simulation Modelling is defining the goals of the simulation model that is to be built. These objectives form the basis of how the data gathered in the previous chapter is used. The main objective of the developed model itself is to achieve the objectives defined prior to the simulation. The objectives of the simulation are the following:

- Find the total lead time for one CMU block.
- Determine the share of VA activities in the total lead time.

- Determine what wall configurations take the longest to be built.
- Determine the bottlenecks in the masonry construction process.

7.3. Assumptions Undertaken

The simulation model was developed with the following assumptions:

- There is no rework on any CMU block. Once a CMU block is laid, the labourers move on to the following CMU block.
- Blocks on the same wall are laid one after the other rather than simultaneously.
- The sequence of steps in the masonry construction process is consecutive.

7.4. Model Input

Since the masonry construction process comprises four steps, these steps are the basis of the developed simulation model. Each step is represented by a task only with its own duration. Doing so would fulfill the objectives and assumptions previously stated. Using K-S values allows for choosing the most suitable continuous distribution for each of the four steps. In this case, we have two hypotheses (shown in equations 3 and 4):

Equation 3:H_0

$$H_0 : The\ data\ comes\ from\ the\ chosen\ distribution$$

Equation 4:H_1

$$H_a : The\ datadoes\ comes\ from\ the\ chosen\ distribution$$

For a sample size of N=31 and a significance level (α) of 5%, the critical value of the One-Sample K-S statistic is 0.238. Hence, for all 4 phases of the masonry construction process, the distribution with the lowest K-S value is to be taken to characterize the duration of the four steps. Having fitted the data obtained in Table 4 on Symphony.NET, we obtained K-S values inferior to 0.238 when applying the maximum likelihood method.

Hence, we can reject H_a and accept the null hypothesis as true. In consequence, we get the following results (mean and standard deviations are in seconds):

Step	Probability Density Function	Mean	Standard Deviation	K-S Value
Take and Place Mortar	Pearson 5	9.979	4.725	0.10449
Place CMU	Weibull	8.984	4.115	0.19198
Knock and Level CMU	Gamma	9.9387	3.058	0.08831
Remove Excess Mortar	Weibull	6.865	3.482	0.12799

Table 4:Distribution of the Masonry Construction Process Steps

7.5. Simulation Model

The current simulation model shown in Figure 14 was built on Any Logic and Symphony.NET and contained the five steps constituting the masonry construction process. The model on Any Logic is used in tandem with the one developed on Symphony.NET. The model built on Symphony.NET is used to extract metrics such as resource utilization. In contrast, the Any Logic Model is used to extract construction lead time—the choice of the two lies in the strength of each one in certain simulation modelling aspects. Any Logic is used for high-level modelling and visualization, and Symphony.NET for low-level modelling purposes. This simulation model is for the first type of wall configuration: a typical horizontal shear masonry wall composed of only horizontal blocks. The entity that this model utilizes is a typical CMU. The CMU block passes through all stations. The blocks and mortar go through all the stations. When the wall is completed, it is grouted. We also have two essential (but non-value adding steps) that are added to the simulation model: Bringing New Pallets of CMUs and Replenish the Mortar Stations. These two steps are essential as the absence of one or both resources stops the work. The internal code in the simulation model reflects such a reality. The model developed is independent of the wall height or total number of blocks in the system, as it is possible to simulate the duration it takes for a wall made of X rows of Y blocks using the simulation model developed.

The different activities in the model are either modelled by a distribution (such as the first four steps of masonry construction) or by average values obtained based on on-site observations and were validated by the superintendent. The first mortar delivery takes 30 minutes. Subsequent mortar delivery would also take 30 minutes. Grouting duration is assumed to be 5 meters of concrete per hour. Hence, the grouting time depends on the size of the CMUs used. In our case, the CMUs are assumed to be 8”x8”x16”. Since no block can be put in a wall sequence without putting the previous block first, it is assumed that the capacity of each activity to be of 1 (1 server in each activity). Blocks are injected into the system to represent the CMU blocks stations, and replenishing the mortar station represents the injection of mortar (as a resource) into the system.

Multiple metrics are extracted from the discrete event simulation model found in Figure 14. The primary metric extracted from the model is productivity based on the assumptions made when developing the simulation model. Productivity is being used as a benchmark for comparison with possible lean interventions.

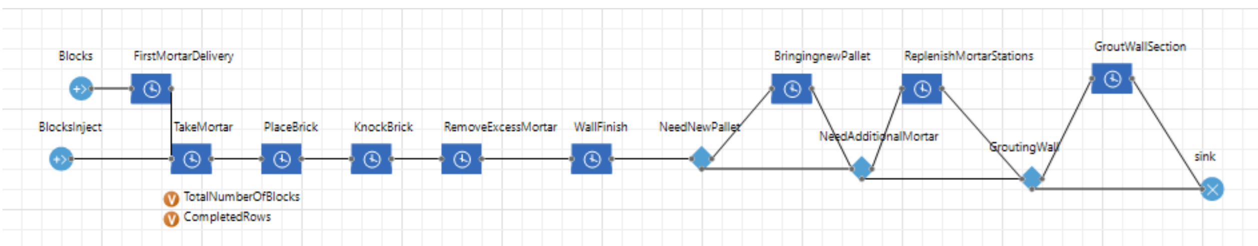

Figure 14: Current Masonry Construction Model

7.6. Verification

The steps adopted in the simulation modelling done in this study are based on the steps developed by Sargent (1992). The first step is the system being studied which is represented by a problem entity. This problem entity is then translated into a conceptual model before being a computerized model in the third step.

Figure 15 shows the process according to Sargent (1992):

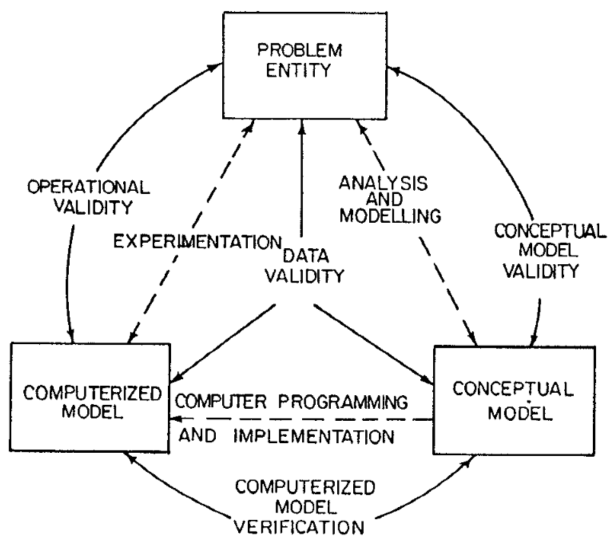

Figure 15: Simulation Modelling Steps (Sargent, 1992)

Following the simulation model's development, verification is needed to ensure that it correctly reflects the reality on the ground. The discrete event simulation model developed is based on the validated Value Stream Map presented in the previous chapter. Moreover, the model follows the same logic of steps undertaken on a construction site. Balci (1994) provides multiple techniques of simulation modelling verification, namely desk checking, white-box testing and black-box testing.

7.6.1. Desk Checking

This technique checks the logic and consistency of the model. The simulation model's code was explained to the site superintendent when explained. The superintendent carefully examined the model to assess the logic and conformity to real-life masonry construction practices. The focus was on verifying the progress of a CMU Block through the model based on the conditions put forward. The checking included checking redundant steps if present, and the proper values were used at the conditional nodes of the model.

Moreover, the model developed in the study is linear and straightforward. The blocks progress through the model after being injected in a linear fashion and do not go through the same step twice. Moreover, the model simulates actual construction site conditions by using conditional nodes to replenish the mortar and bring new pallets. This logic is also validated by the superintendent on site.

7.6.2. Black-Box testing

This technique focuses on comparing the output and input of the simulation model disregarding all internal processes of the simulation model. Multiple input scenarios were used to examine the behaviour of the simulation model. In our case here, the number of blocks per row and the number of rows were changed. The black-box testing confirmed the model's adherence to invariance principles. In other words, we are checking for the comparison between the input and output of elements in the system. The number of blocks in the system remains constant regardless of all the steps undertaken in the simulation model. The output of the model (number of blocks laid) also matches the numbers input in the model when choosing the number of blocks per row and number of rows.

7.6.3. White-Box Testing

This technique checks the interaction of the elements in the simulation model. Knowing that the objective of the simulation model is to evaluate current masonry construction practices, it is essential to make sure that the different elements in the simulation model are interacting correctly. The block moves from one station to another until the pallet is empty. At that point, replenishing happens. The mortar is delivered when the mud boards are empty, and the system halts until replenishment. Also, the number of blocks in the system passes through all the appropriate steps and conditional nodes before being counted. The number of blocks passing through the system was checked by looking at the count of entities at each step in the masonry construction process. It was found to be uniform and matches the total number of blocks in the system. The site superintendent validated the interactions between the different elements for their coherent interactions, which affirms the robustness and reliability of the simulation model developed.

7.7. Validation

Model validation is needed to ensure that the model developed is similar to real construction site conditions. This step is essential as having a simulation model that mimics real-world conditions since it will be used as a benchmark for pinpointing the different problems in construction site conditions and subsequent simulation models developed for the proposed lean interventions. Sargent (2010) provides multiple validation techniques: face, internal, and face validity.

7.7.1. Face validity

First, the simulation model's face validity was assessed. This technique is based on the validation of the results by expert opinion. In our case here, masonry construction industry practitioners and, more specifically, the construction site superintendent where the data collection happened. During the face validity process, the model's results (in our case here, the average number of blocks per day) were confirmed to be like the productivity of one mason.

Hence, the simulation model was presented to the superintendent, who agreed that the model results were correct compared and represented construction site conditions. Moreover, all results were justified, and any questions or ambiguities were cleared up and incorporated into the model that was updated iteratively.

7.7.2. Event Validity

This technique relies on comparing what is modelled to the real system. The model obtained was run, and the daily productivity for one mason was found to be similar to historical productivity rates provided by the site superintendent. Moreover, it was clear that the grouting and the provision of the CMUs and mortar constituted essential portions of the total masonry construction time. Hence, the model's outputs juxtaposed with the productivity rates on construction sites. Concerning the construction lead time, it is expected to have some wait as the resources are brought to be used, whether it is the mortar or the CMUs. This inclusion of this event further validates the model by mimicking actual periods of waiting (Non-Value-Adding time) that are intrinsic to masonry construction practices and operations.

7.7.3. Internal Validity

This technique relies on the variability between the runs of the simulation model. The average construction lead time variability hovered around 5% between the different runs. This little variability between the different runs proves that the system is not unpredictable but rather acceptable. The runs performed were done with varying numbers of blocks per row and rows in total to check the model's reliability. The results were deemed consistent and acceptable as they all showed the same construction lead time variability. Ensuring consistent outputs and small variations further confirms the stability of the model and, by extension, its internal validity.

7.8. Results and Discussion

The model was run 1000 times on Symphony.NET to get accurate results on the system's behaviour. The results of the simulation run on both simulation software permit us to understand how the different elements on the construction site interact. The validated results were used as a starting point for the proposal of lean improvements in construction site conditions. In our case, the sources of waste identified are later tacked and simulated to understand their overall impact on the entire system and construction site conditions. The daily production rate, overall construction lead time and station utilization are derived from the simulation model and analyzed in the following sections of this chapter.

The essential value-adding activities were simulated to obtain the station utilization of each of the different masonry construction activities:

7.8.1. Daily Productivity Rate

The number of blocks laid is done for every 7 hours of work to reflect construction site conditions to compare to the average daily production rate of the masonry construction process. Moreover, doing so helps us identify the variability in the construction process and see whether the simulated model mimics real-life conditions.

Figure 16 shows us the number of blocks laid daily, assuming a 7-hour workday for an entire workweek composed of six days. On the seventh day (Sunday), the number of blocks laid amounts to zero since no work is performed that day, and the workweek is assumed to run from Monday to Saturday. The daily productivity rate here ranges from 39 to 52 blocks per day, with a mean of 47 blocks per day. The current average number of blocks laid on site is 50 blocks per day which run on par with the results obtained in the simulation model. The production drops to the low end of the daily production range during the week due to replenishing mortar and CMU blocks stations, as seen on Day 3 and Day 5. Days with higher productivity are reached on Days 2 and 4 when the number of blocks laid hovers around 51 blocks per mason. Such variability is in line with expectations due to variability in masonry construction on construction sites. The average daily production rate is 5.57 blocks/hour.

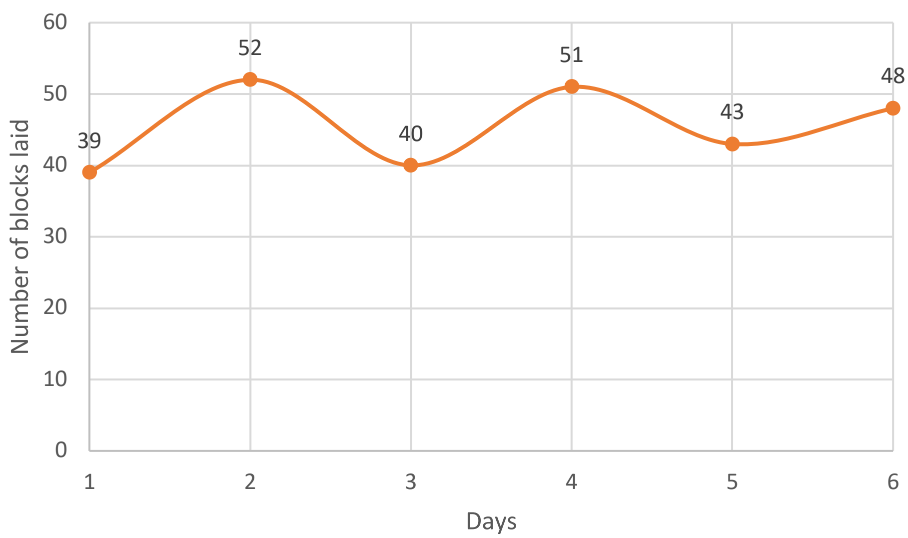

Figure 16: Daily Productivity

7.8.2. Construction Lead Time

The simulation model allows us to know the time each CMU block stays through the entire system. In our case, it helps us get the total construction lead time for the total number of blocks that pass through the system. This metric would enable us to understand the current state of the masonry construction process and pinpoint whether we have a stressed construction system. Suppose a CMU block stays in the entire system for a longer amount of time. In that case, we can deduce that we have variability in the masonry construction process and qualify the construction system as stressed. The lead time also enables us to understand the causes of the stress in the masonry construction process. In other words, a CMU block will be laid on a wall, whether done on Day 1 or Day 6, but the difference lies in the amount of time it takes to put the CMU block on the wall being constructed. If a CMU block takes longer to exit the construction system, it shows it is not performing optimally.

Figure 17 shows the lead time for every CMU block to go through the entire masonry construction process. On the x-axis, we have the number of blocks laid to erect a wall. It can be noted that the number of blocks is ascending on the x-axis since construction is being done and the wall is being built. This number reflects the reality of masonry construction on construction sites. The first CMU block stays the longest in the system as we must wait for the first mortar mixing and delivery, assuming we are starting the masonry construction on day 1 (Monday). The sudden jump in Lead Time, as shown in Figure 17, is due to the waiting needed to replenish the mortar station or bring a new pallet of blocks before moving on. When either or both happens, we get these variable lead times in masonry construction. As the graph shows, this sudden jump represents a waste of time on the construction site when idling happens on the wall being built while the equipment carries either the mud tub of mortar or the pallets. Such waste is a manifestation of the stressed system of construction as it leads to delays in the construction of the wall.

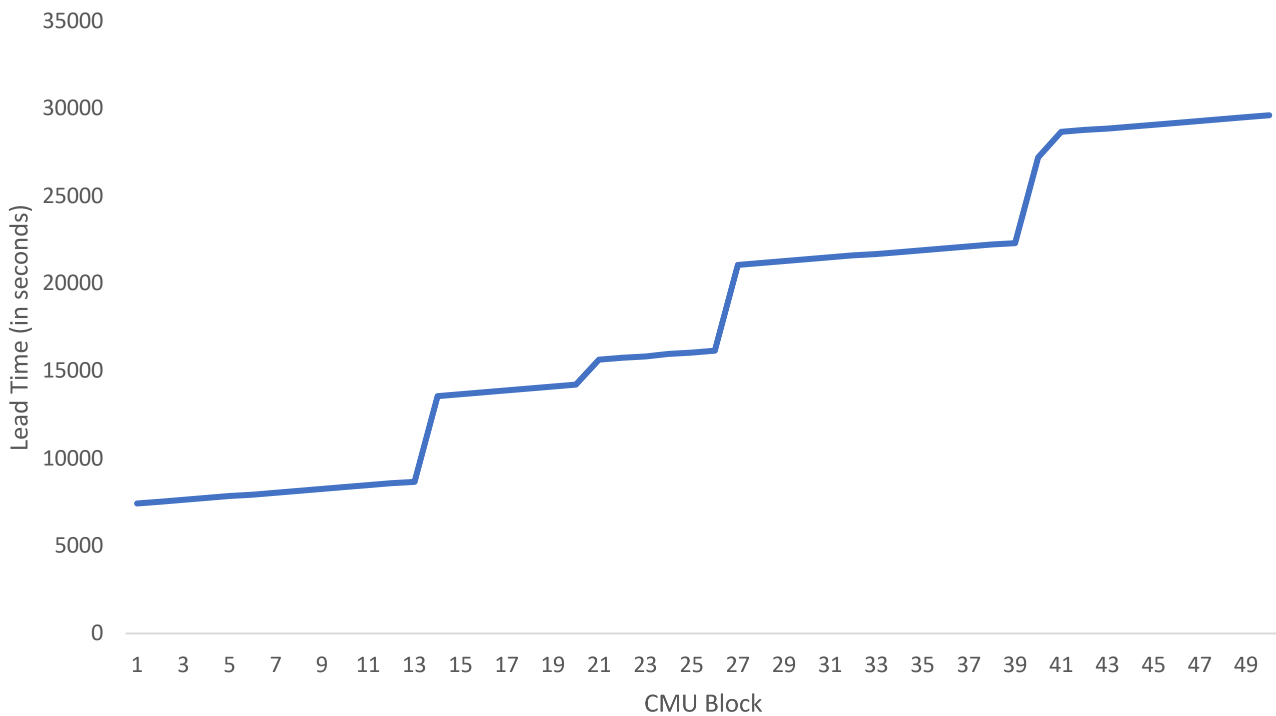

Figure 17: Construction Lead Time

7.8.3. Utilization rates

The utilization rate of a certain masonry construction activity signifies the percentage of a certain activity used when performing the masonry construction process. In our case, the station utilization comprises the five essential masonry construction steps (removing mortar, placing the CMU block, knocking and levelling, removing excess mortar, and wall finish). Just because a CMU block is undergoing a specific step of the masonry construction process does not mean it is doing so effectively. The rate would enable us to know if a particular step takes more time than the rest of the steps to be done. When a step of the masonry construction process is very used (high average utilization) or barely used (low average utilization), we can deduce which steps of the masonry construction process would be considered a bottleneck and hinder the overall performance of the masonry construction process. Figure 18 shows the steps affecting singular CMUs:

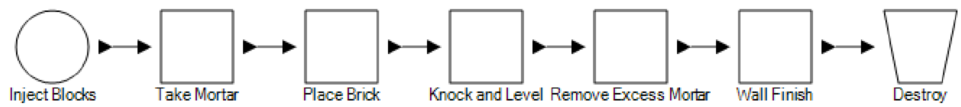

Figure 18: Simulation model for average utilization

The graph (Figure 19) below represents the average utilization (the mean utilization rate and standard deviation of each station) for the steps affecting individual CMUs in the masonry construction process. Based on the results obtained, it can be concluded that taking the mortar is the resource bottlenecking the system since it is present in three of the five steps that constitute the masonry construction process. Moreover, wall finishing concerns the entirety of a wall and includes activities such as jointing the wall, painting the wall etc., which are not considered foundational construction steps of a wall. This means that an upstream bottleneck affects the entire system as the process is undertaken. We can also notice that removing excess mortar is the step that is clearly underutilized, with an average utilization rate of 5.4%. We can hence say that such a step is rapid and does not affect the overall flow but is still related to the use of mortar which may be considered problematic in our case here since the handling of the mortar as a resource is present in the first and last step concerning individual CMUs. Such results can allow us to deduce that the system is not well balanced, with some steps taking longer than others while seeing a hindrance in construction flow due to using mortar as a resource in the masonry construction process.

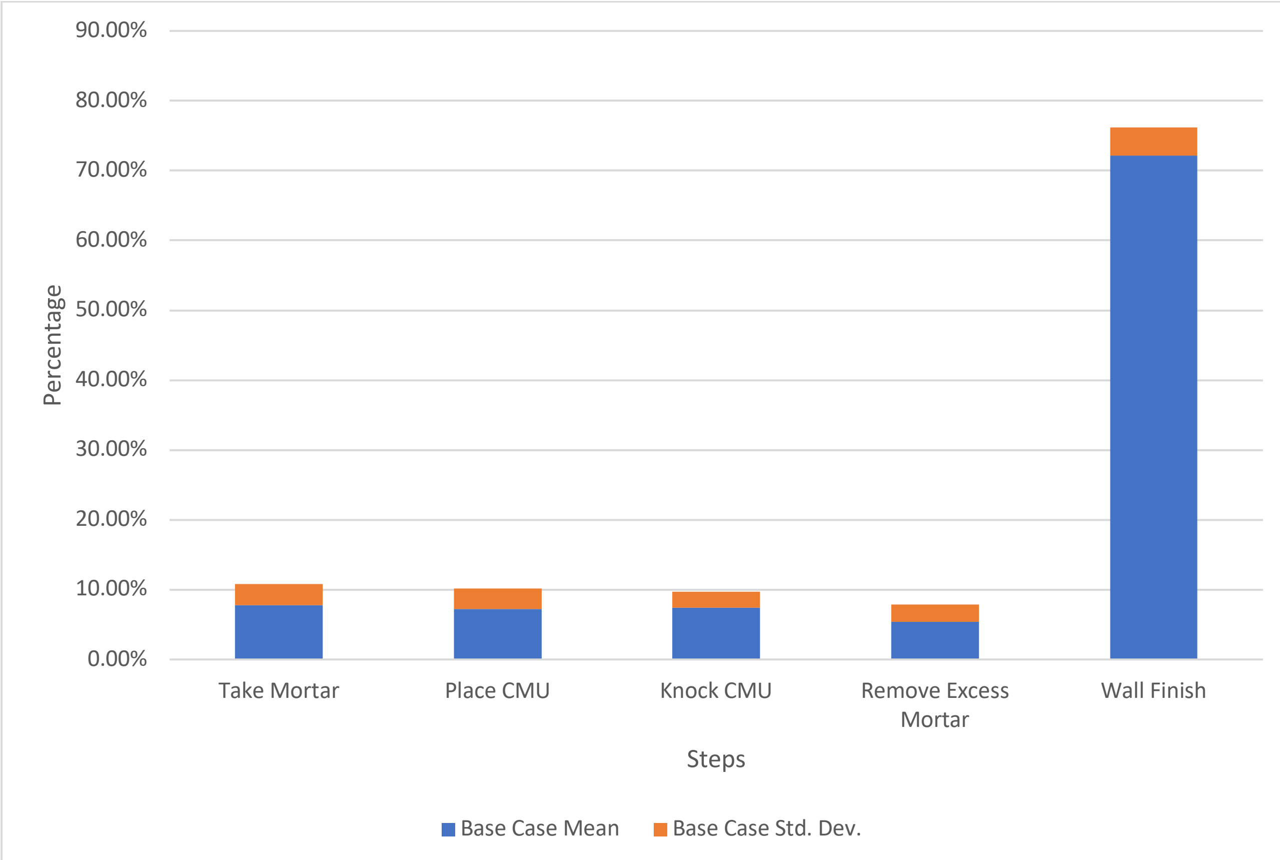

Figure 19: Station Utilization

Based on the simulation result, the coefficient of variation was obtained and calculated respectively. The coefficient of variation expresses the variability in a process. In our case, it symbolizes the duration it takes to perform one of the masonry construction activities. The greater the coefficient of variation, the more significant the difference in time (duration) it takes a mason to perform such a task which indicates non-standardized work practices to perform such a task. If a coefficient of variation is closer to 100%, it indicates that a certain step has much variability in its execution and is problematic. The closer to 0%, the coefficient of variation is, the more uniform and predictable the execution of a specific step.

As a potential improvement, it is possible to explore the option of reducing the coefficient of variation for each station individually rather than harmonizing the coefficients of variation. Reducing the coefficient of variation would enable us to improve the system's performance.

Table 5 shows the coefficient of variation in the station utilization of each of the four steps affecting single CMUs:

Step	Coefficient of variation
Take and Place Mortar	38.5 %
Place CMU block	42%
Knock and Level CMU block	31%
Remove Excess Mortar	47%
Wall Finish	6%

Table 5:Coefficient of Variation for Different Stations

As seen in Table 5, Removing Excess Mortar has the highest coefficient of variation, standing at 47%, because of the unpredictable amount of mortar taken in each trowel.

7.9. Conclusion

In this chapter, the discrete event simulation modelling of the masonry construction process was performed on both Any Logic and Symphony. NET. The chapter details all the assumptions made to build the model as well as the goals and objectives of the simulation model. Furthermore, the model inputs, validation and verification were explained in detail. The metrics obtained after analysis of the simulation model of the masonry construction process were the following: daily productivity rate, construction lead time and utilization rates. The obtained metrics allowed us to infer that the system is not functioning correctly with variations in the number of blocks laid every day (lack of consistency), variations in the construction lead time of certain blocks due to idling (improper resources delivery and handling), variations in the utilization rate of each of the steps in the masonry construction process.

The Simulation Modelling allowed the identification of a stressed construction system with variability governing the entire masonry construction process. Indeed, the logistics on site for material handling proved to be problematic due to the waiting time for construction pertaining to certain CMU blocks. Based on the results obtained in this chapter, masonry construction improvements can be suggested and compared. Chapter 6 details Masonry Construction Improvements.

8. Masonry Construction Improvements

8.1. Introduction

The in-depth analysis of the current masonry construction process is crucial in proposing ways to improve the system using lean principles. It is important to note that change cannot happen before a complete understanding of the processes at hand. No change can be made without a good grasp of the current construction practices. Only then can lean principles be used to alter the system of construction. Lean theory is the main driver for the proposal of ways to reduce waste and add value to the customer. The Toyota Production System (Liker 2021) defines two crucial principles that were used to come up with alternative systems of masonry construction:

1. Principle 6: *"Standardized tasks are the foundation for continuous improvement and employee empowerment."*

Making sure the masonry construction process does not have high internal variability when it comes to the process. Masonry construction should be an activity that is as uniform as possible. Using standard procedures and equipment would reduce variability and increase the flow and creation of value on a construction site. It is necessary to ensure that emphasis on standardized and reproducible procedures is considered.

2. Principle 13: *"Make decisions slowly by consensus, thoroughly considering all options; implement rapidly."*

Drastic changes to a slowly changing industry are not a decision taken by a single entity when the effects would touch on an entire industry. Instead, the decisions are taken based on multiple entities coming together to conclude whether a particular solution has merit in terms of value. It is a team effort. This principle was applied from the very early research stages, with multiple visits to a construction site. After observing the moving parts on-site, the problem was formulated, and data was collected. Second, the hackathon was organized at the University of Alberta with the participation of industry practitioners. Third, the results and solutions were proposed to practitioners in the masonry industry for their feedback.

The solutions proposed completely change the traditional masonry construction process and reform it in many aspects: from the tools used to the material to the steps undertaken to build a wall composed of CMUs. The solutions suggested by the many participants in the study were the basis of the testing of viable ways to reform the masonry construction process. The solutions suggested revolved around the idea of the creation of a new system for masonry construction. One of the ideas was the implementation of a modular construction system. Another idea jolted around the creation of a new masonry block. Figure 20 shows a conceptual, preliminary new masonry block to be used on construction sites. Another idea hovered around creating a hybrid semi-autonomous system where a robot would help a mason with tasks on-site to reduce human effort. Figure 20 shows a stage in the development of the masonry block.

Figure 20: Interlocking Masonry Block Development

The potential solutions were tested. It is important to note that swift action and decision regarding the best course of action to take was crucial since it would form the basis for an actual novel masonry construction system. The idea of receiving feedback and ideas is primordial in a lean context as it is about developing a culture where everyone contributes and is heard. Such a culture leads to the generation of value-creating solutions that tie up with the lean concept of *Kaizen*.

To implement any of the proposed solutions, a cultural shift needs to happen on a construction site where a culture change is usually a lengthy process. However, changes can percolate into the construction industry with the right motivation (increased value, decreased waste, and human effort). Such a culture shift is led by empowering the employee to think and contribute to improving the masonry construction process and construction practices.

This chapter touches on the potential solutions to the current masonry construction process as well as on the behaviour of the system when presented with the potential solutions from a productivity perspective. Such a behaviour is derived from the results of the simulation models developed. The modelling will allow us to accompany a qualitative improvement of construction site conditions with quantitative results.

8.2. Proposed Solutions

Following the analysis and validation of the base case scenario (the traditional masonry construction process), three options are proposed to implement improvements from a lean construction perspective.

8.2.1. Intervention 1: Modular Construction

The first intervention consists of using modular construction. In this option, sections (panels) of 24 blocks are built using the traditional masonry construction process with some modifications: the panels are done on the ground (instead of at an altitude). They are grouted after being built and consequently lifted, assembled, aligned, and levelled. The steps were extracted from recordings done when the panels were being put in place. The process does not involve the use of scaffolding or a hydro platform but requires a crane to lift and a scissor lift for the two masons needed per section of the wall being built. Having observed the process, it was simulated to compare this method's total time and productivity with the traditional masonry construction process. Compared to the traditional masonry construction process, the critical change here lies in the absence of mortar delivery (whether at an altitude or not) due to the modular property of the assembled section. In our case, the modular sections produced are done on ground level. The removal of such a step allows the reduction in idling time on site (as seen in the construction lead time in the previous chapter) as well as a decrease in variability between the time it takes to put the blocks in the wall being built. The model taken into consideration here is based on the modular panels developed by Elsayed et al. (2022).

The simulated model's major difference from the base-case scenario is that it does not require lifting the material above ground when building the panels. Moreover, the grouting is done after the panels are fully completed. The time study conducted for the base-case scenario was used as a basis for the model since the activities' durations were previously collected, and the improvement was based on the transportation issues arising from the constant moving of material around a construction site. The "Unit Lift" time was derived from observations during the wall assembly. The standardization of the creation of the panels (in our case here, made of 24 blocks) and their fabrication on site before assembly even happens relieves the time pressure put on a mason to finish a section of a wall to stay on schedule. Indeed, the panels can be created and put in storage up until the time their use is needed for construction purposes.

8.2.2. Intervention 2: New Interlocking Masonry Block

In this option, blocks (shown in figures 21 and 22), the issue of mortar usage is tackled by creating an interlocking CMU blocks system. The system would only need to stack the blocks on top of each other to construct the wall. Grouting may be done if required. The steps undertaken here constitute a simplified masonry construction process based on the traditional one. In this process, safety is also touched upon as lifting the mortar to an altitude has been eliminated.

Moreover, the new step sequence only involved placing the blocks and finishing the wall. Based on these assumptions, the process using interlocking blocks was simulated to get the total time and productivity to be contrasted and compared with the traditional masonry construction process. The block used here is developed by Camila Patiño, an MSc student at the University of

Alberta.

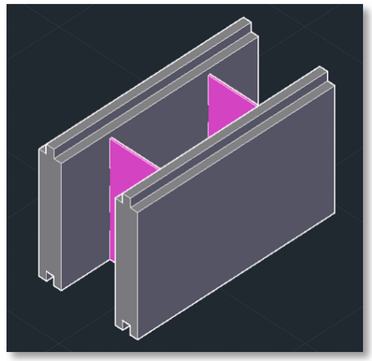

Figure 21:Interlocking Block

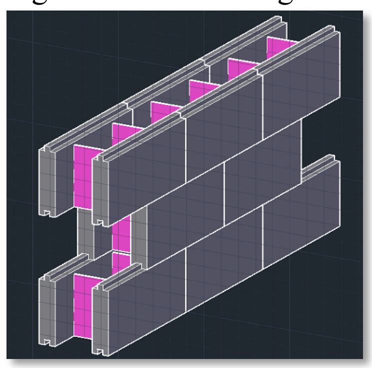

Figure 22: Stacking of Interlocking Masonry Blocks (Courtesy of Camila Patiño and her supervisor, Dr. Carlos "Lobo" Cruz Noguez)

8.2.3. Intervention 3: Semi-autonomous Masonry Construction System

The potential creation of a semi-autonomous construction system would create a new sequence of masonry construction steps where waste is reduced based on lean interventions. This system would involve using a robot in collaboration with a mason to simplify the masonry construction process further and ensure appropriate task allocation between the robot developed and the mason.

8.3. Simulation of the Interventions

8.3.1. Intervention 1: Modular Construction Simulation

Figure 23 below shows the simulation model developed to simulate the behaviour of modular construction on site and consequently get the productivity and compare it with the productivity of the traditional masonry construction process. It is important to note that the time to get mortar is not considered in this intervention since it is assumed that the mortar is mixed directly next to where the unit is made. The pros and deltas (from a lean perspective) of modular construction were derived through observations.

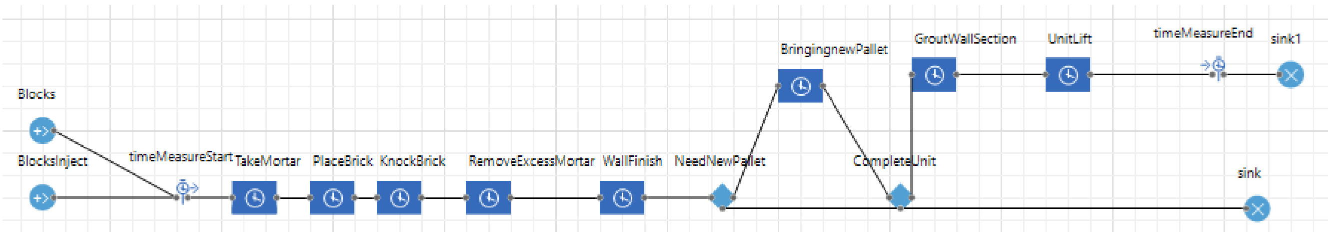

Figure 23: Intervention 1 Simulation Model

Following this potential lean solution, we significantly drop the time needed for masonry construction. Indeed, a 46% decrease in the time needed to lay one modular unit is noticed after running the simulation model in Figure 23 above. Table 6 shows the main differences between the base case and Intervention 1.

Property	Base Case: Traditional Masonry construction process	Option 1: Modular Construction
Reduce human effort in CMU block handling.	N/A. Significant effort is made to complete the masonry construction process.	In new sequence, decreased used of hydro platform. Construction is done on ground level. Each modular unit is comprised of 30 CMU blocks.
Automate delivery packages (panelized or block by block)	No automation, blocks are manually laid on site.	Quantities needed can be calculated in advance and reduce lead time of procurement and delivery.
Ease of handling (robot and human compatible)	No use of robot. Blocks are heavy and are consequently hard to handle.	Possible use of robot in material handling
Weight of unit	Standard CMU Block 28 lbs	Standard CMU block 28 lbs
Masonry construction process	1. Take and Spread Mortar 2. Place CMU block 3. Knock and Level CMU block 4. Remove Excess Mortar 5. Joint and finish wall 6. Grout Wall	New Process incorporating lifting the modular units up and placing them where wall needs to be built.
Safety	May present safety hazard onsite if mortar and CMU block transportation is not done correctly: falling hazard.	Safer as modular units are made on ground level than at an altitude.
Labour	One mason per every ten lineal feet of space.	2 masons are needed per section of the wall being built.
Time	29650 seconds for 50 blocks	30290 seconds for 5 panels of 24 blocks each
Quantity (Productivity)	593 seconds/block.	320 seconds per block. 46% decrease in time needed. Hence, Increased productivity.

Table 6:Comparison with Intervention 1

8.3.2. Intervention 2: New Interlocking Masonry Block Simulation

Figure 24 below shows the simulation model developed to simulate the behaviour of masonry construction using interlocking masonry blocks on site and consequently get the productivity and compare it with the productivity of the traditional masonry construction process. The pros and deltas (from a lean perspective) were derived through observations. In this scenario, we can look at the masonry construction process found in the base case and find similarities such as "Place CMU block" but also differences due to the nature of the interlocking block that does not need mortar as a resource. Only blocks are needed, and the simulation model developed reflects such a reality. Moreover, the duration of placing the CMU block is taken to be the same as the duration it takes to lay blocks in the traditional process, as the new CMU block is similar in shape to the traditional 8"x8"x16" CMU block. Furthermore, we can remove the replenishing of the mortar station since no mortar is used in this intervention. Removing mortar as a resource enables us to reduce variability in the process as the process is only comprised of placing the CMU block and grouting, if necessary, after completing a wall or a section of a wall.

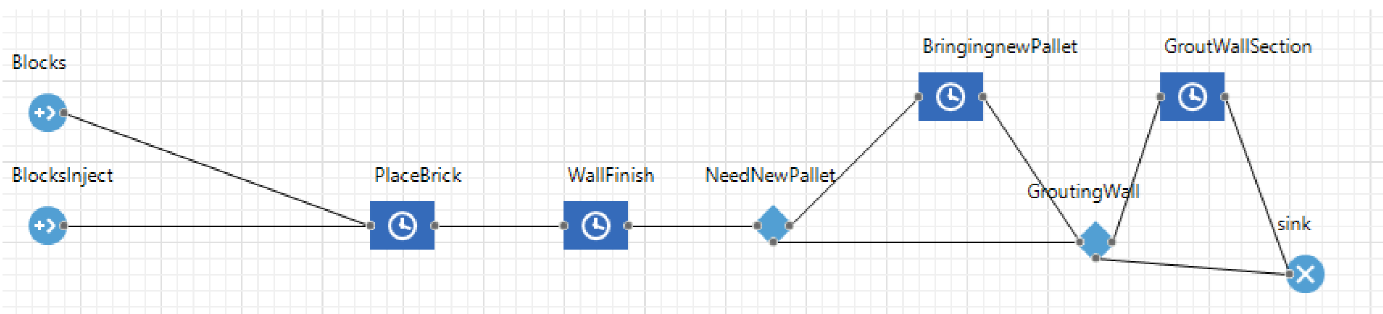

Figure 24: Intervention 2 Simulation Model

Following the implementation of this potential lean solution, we have a significant drop in the time needed for masonry construction. Indeed a 22% decrease in the time needed to lay one block is noticed after running the simulation model found in Figure 24 above. Table 7 shows the main differences between the base case and Intervention 2.

Property	Base Case: Traditional Masonry construction process	Option 2: New Block
Reduce human effort in CMU block handling.	N/A. Significant effort is made to complete the masonry construction process.	Interlocking block, no need to use mortar anymore.
Automate delivery packages (panelized or block by block)	No automation, blocks are manually laid on site.	Quantities needed can be calculated in advance and reduce lead time of procurement and delivery.
Ease of handling (robot and human compatible)	No use of robot. Blocks are heavy and are consequently hard to handle.	Possible use of a robot in material handling
Weight of unit	Standard CMU Block 28 lbs	New block 17.3 kg
Masonry construction process	1. Take and Spread Mortar 2. Place CMU block 3. Knock and Level CMU block 4. Remove Excess Mortar 5. Joint and finish wall 6. Grout Wall	1. Place CMU block 2. Finish Wall 3. Grout Wall
Safety	May present safety hazard onsite if mortar and CMU block transportation is not done correctly: falling hazard.	Units are stacked just like in the traditional process. However, added safety as no lifting of mortar tub at an altitude is needed→ Reduced hazards from using heavy equipment on site.
Labour	One mason per every ten lineal feet of space.	1 mason that stacks the blocks on top of each other and adjacent to each other
Time	29650 seconds for 50 blocks	Considering the use of traditional masonry construction process values: assumed to time to place blocks finish wall and grouting the wall. 23067 seconds for 50 blocks
Quantity (Productivity)	593 seconds/block.	462 seconds/block. 22% decrease in time needed per block.

Table 7:Comparison with Intervention 2

8.3.3. Intervention 3 Simulation: Semi-autonomous Masonry Construction System Simulation

For this simulation, assumptions were also made to get results. The properties of the robots were assumed and translated into simulation elements to be modelled. In this simulation, it is assumed that the mason does not need to be involved in material handling. Rather the robots would assist in transporting the necessary resources (CMUs, mortar) hence applying a just-in-time inventory system on-site. This intervention targets on-site material handling by using a robotic platform that gets blocks from inventory to the location where masonry construction is being done and another robot that transfers the blocks from the inventory pallet onto the robot platform. The first robot would be activated when needed to load the blocks onto the platform, and the platform could go back and forth when the inventory is low. The worker would activate the platform when needed. It is important to note that each mason should have two stations of CMU blocks to avoid idleness and successfully implement just-in-time delivery. On another note, this intervention allows the reduction of physical strain on the mason and efficient planning of material scheduling.

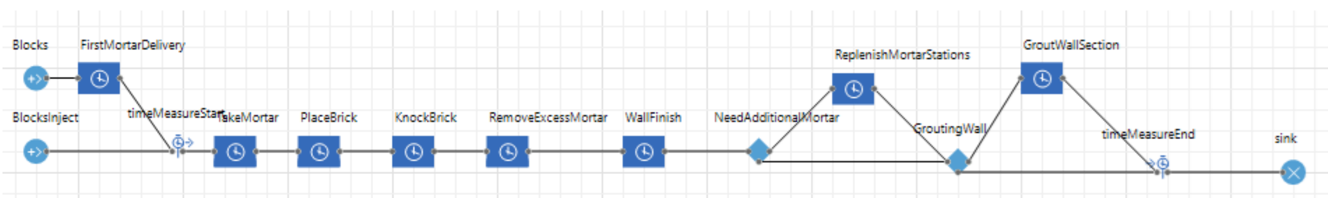

Figure 25: Intervention 3 Simulation Model

We drop the time needed for masonry construction following the implementation of this potential lean solution. Indeed, a 13.5% decrease in the time needed to lay one modular unit is noticed after running the simulation model found in Figure 25 above. Table 8 shows the main differences between the base case and Intervention 3.

Property	Base Case: Traditional Masonry construction process	Option 3: Hybrid System: Robotic Construction + CMU block: Potential semi-autonomous system.
Reduce human effort in CMU block handling.	N/A. Significant effort is made to complete the masonry construction process.	Reduced effort in the handling of CMU block, typically done by the mason.
Automate delivery packages (panelized or block by block)	No automation, blocks are manually laid on site.	Can be used with both traditional CMU blocks and new interlocking masonry blocks.
Ease of handling (robot and human compatible)	No use of robot. Blocks are heavy and are consequently hard to handle.	Robot handling of the CMU, human supervision.
Weight of unit	Standard CMU Block 28 lbs	Standard CMU 28 lbs /New Block
Masonry construction process	1. Take and Spread Mortar 2. Place CMU block 3. Knock and Level CMU block 4. Remove Excess Mortar 5. Joint and finish wall 6. Grout Wall	1. Robots gets blocks 2. Place CMU block 3. Human monitors and controls robot and intervene when needed.
Safety	May present safety hazard onsite if mortar and CMU block transportation is not done correctly: falling hazard.	Use of robot reduces human effort on site and consequently potential injury hazards that may arise from activities on construction sites.
Labour	One mason per every ten lineal feet of space.	1 monitor for robot conducting work in conjunction with monitor. Blocks are stacked up on top of each other and next to each other.
Time	29650 seconds for 50 blocks	25652 seconds for 50 blocks
Quantity (Productivity)	593 seconds/block.	514 seconds/block. 13.5% decrease in time needed. Hence, increased productivity.

Table 8:Comparison with Intervention 3

8.3.4. Combination of Interventions

Following the simulation of the base case scenario and the three interventions, it is essential to compare them to find what would be the most optimal solutions given both the original process and chosen lean interventions to improve construction site conditions. The construction productivity rate (per CMU block) and construction lead time were compared and analyzed. Moreover, the combination of the chosen interventions was also simulated and analyzed. The recommendation made at the end of this chapter would be to the intervention (or combination of interventions) which would yield the most optimal result for improving construction site conditions.

The possible intervention combinations are the following:

- Intervention 1+2: Make a modular unit using interlocking blocks.
- Intervention 1+3: Make modular Units and use robots to help in material handling on site.
- Intervention 2+3: Use Interlocking blocks and robots to help in material handling on site.
- Intervention 1+2+3: Use interlocking blocks to make modular units and robots to help handle on-site materials.

8.3.4.1. Intervention 1+2

In this intervention, there is no need for the use of mortar since we are creating modular units using interlocking blocks. There is no need for mortar in our case here. The model developed here comprises steps existing in the traditional masonry construction process but lacks some (such as the steps related to mortar: Take Mortar, Knock and Level CMU block, and Remove Excess Mortar). This combination also lacks bringing new mud tubs of mortar due to the absence of the use of this resource due to the usage of interlocking blocks in this scenario. Figure 26 shows the model developed:

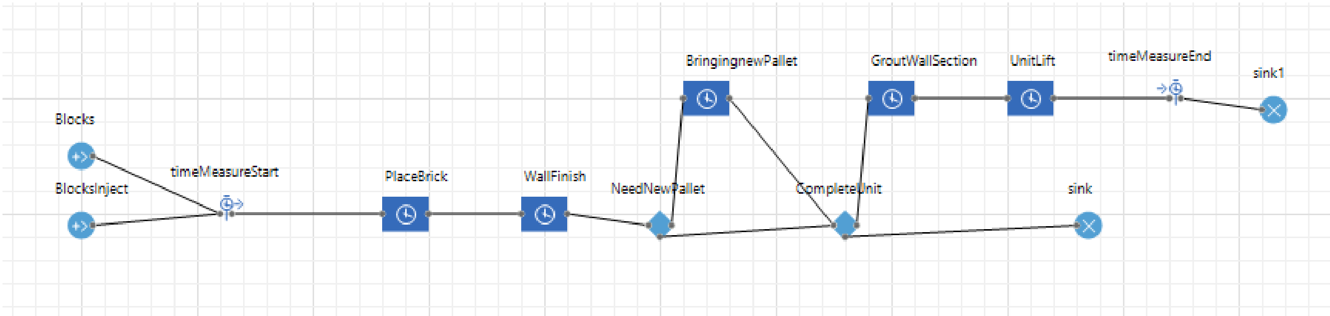

Figure 26: Interventions 1+2 Model

8.3.4.2. Intervention 1+3

In this intervention, we do not need to bring new pallets as the robot platform is doing so. It is worth noting that we are still using the traditional masonry construction process in this intervention. However, the difference lies in the time the modular units are done. By doing them in advance, we avoid the need to bring new pallets (thereby reducing our lead time) and constantly replenish the mortar stations. Moreover, the work is not done at an altitude. Figure 27 shows the model developed:

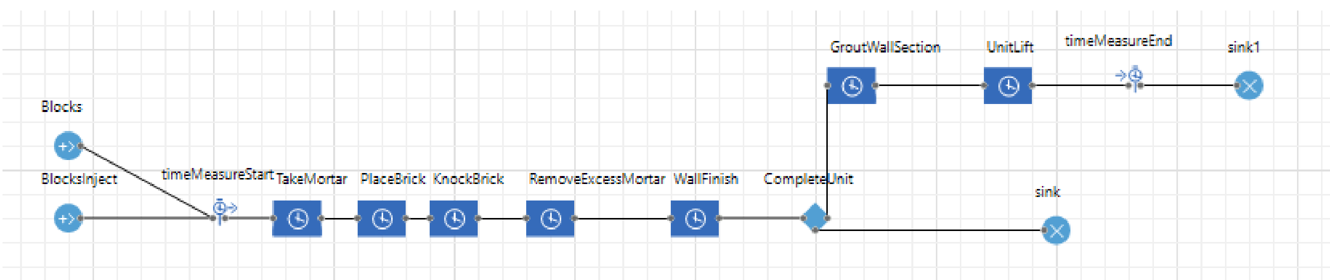

Figure 27: Interventions 1+3 Model

8.3.4.3. Intervention 2+3

In this intervention, we do not need to transport new pallets as the robots will do so. Moreover, interlocking blocks allow one to skip the steps related to mortar handling on the construction site. Figure 28 shows the developed simulation model for combining interventions 2 and 3:

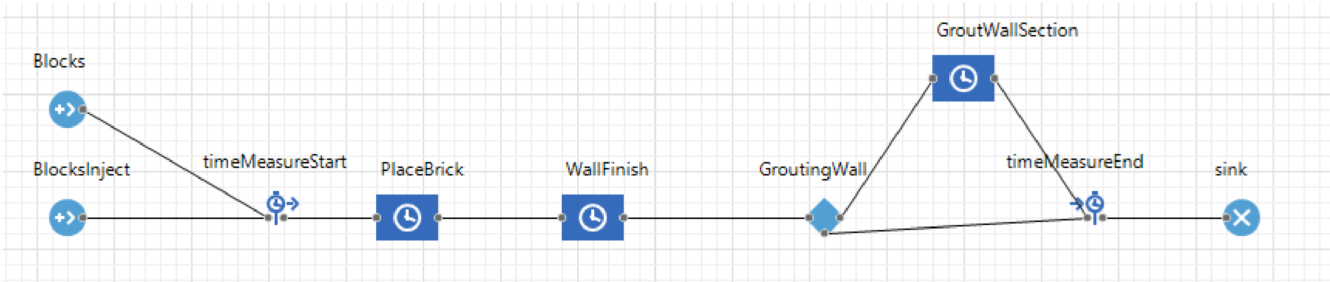

Figure 28: Interventions 2+3 Model

8.3.4.4. Intervention 1+2+3

This option combines all the proposed lean improvements are combined. We notice the lack of mortar usage in the process and the straightforward linear path taken to complete the units and put them as part of a wall. Figure 29 shows the developed simulation model for combining interventions 1, 2 and 3:

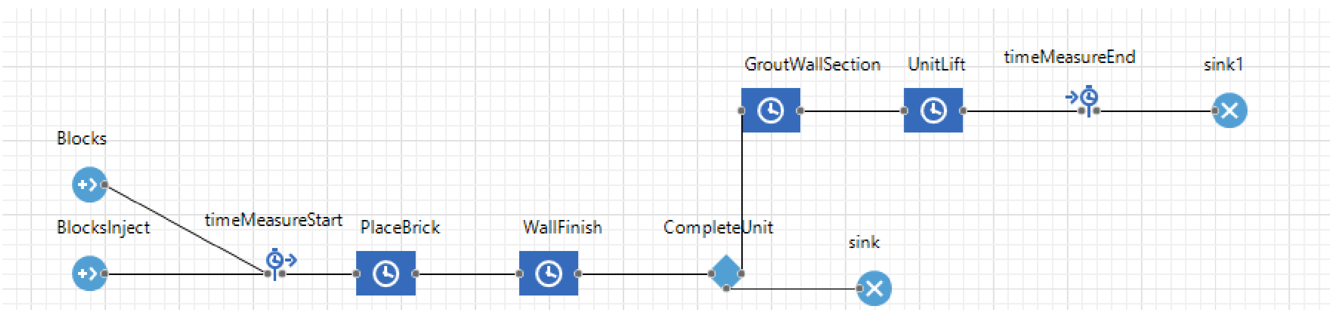

Figure 29: Interventions 1+2+3 Model

8.4. Results and Discussion

The basic metric used in this study for comparison is time. It is, however, worth mentioning that other factors, such as structural, thermal, and industrial, should be included to get a complete analysis. In this study, the focus is on time as a factor since, as a factor, time is also indicative of overall performance on construction sites.

8.4.1. Construction Lead Time

When simulating any of the 3 three interventions (and their respective combinations), we noticed an improvement in lead time. Figure 30 shows the PLT when considering the different improvements. Since each modular unit is composed of 24 traditional CMUs, the time it takes to complete two modular units (48 CMU blocks) was taken to be plotted for all the interventions as well as the base-case scenario. To plot, the time it takes to complete one modular unit was divided by 24 for each of the two modular units. The purple line shows the base case scenario (the traditional masonry construction process). We can see in the plotted graph that the base case has the highest construction lead time out of all the masonry construction processes. Using the robot alone (intervention 3) has the least impact on the system when implemented.

The intervention that had the most impact on the total lead time is Intervention 1, as it removes the need to wait for mortar constantly. Moreover, the modular units made of 24 blocks were advantageous because they allowed faster construction and lifting times rather than having idle time when assembling. Intervention 2 and Intervention 2+3 still exhibited constant idle time for certain blocks due to the depletion of the stock of materials when masonry construction. The combination of Interventions 1, 2 and 3 together showed to be the most promising at reducing the construction lead time due to the significant improvement of construction site conditions whether at a macro level (material handling on site) or micro level (fewer steps compared to the traditional masonry construction process).

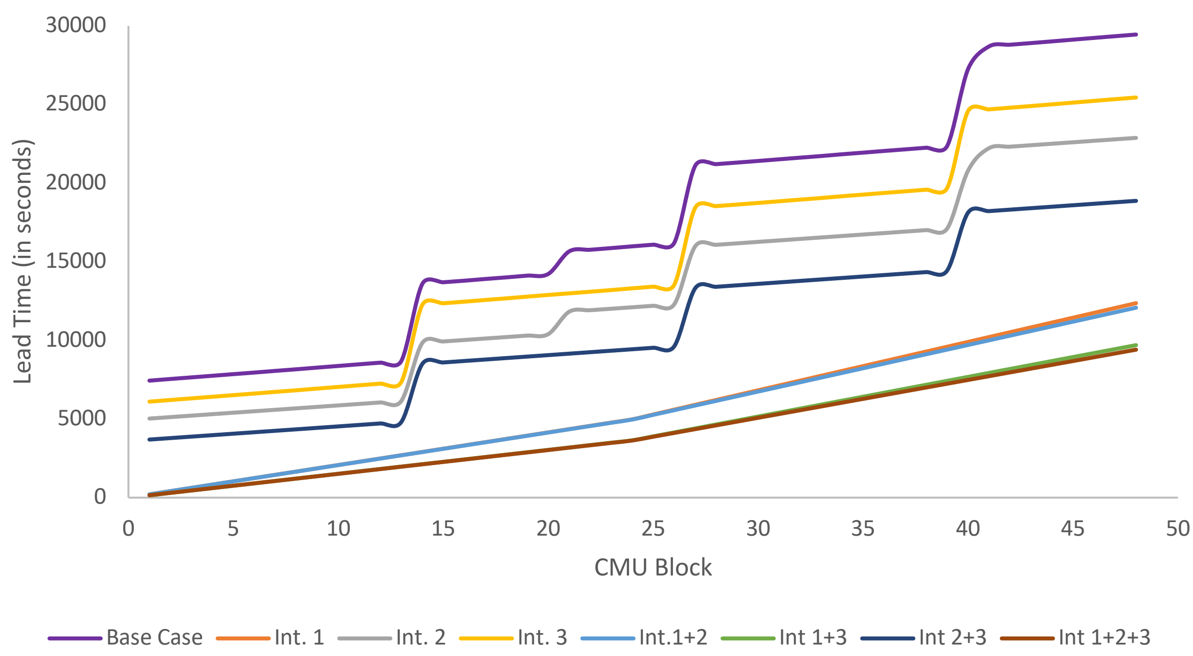

Figure 30: Construction Lead Time

8.4.2. Construction Productivity Rate

The construction daily productivity rate was derived for each intervention (and their respective combinations). The productivity was calculated in seconds/block for each. The simulation models were run, and an average number of blocks per day laid was obtained for 40 days. We obtain the following results.

The dark blue line presents the average daily number of blocks laid. It can be noticed that the traditional masonry construction process has the lowest daily construction productivity rate when compared with the interventions made. As a standalone metric, the productivity rate is insufficient to decide if a system works optimally. A high productivity rate can also mean worker exhaustion if the process is not sustainable. However, it is still an important metric to consider when choosing an alternative. The proposed lean solutions aim to improve construction site conditions that are both sustainable and time efficient. Figure 31 shows the daily construction productivity rates and how well the lean interventions could ameliorate the rate compared to the base case scenario. Intervention 1+2+3 ameliorated the rate the most, while intervention 3 alone had minimal impact on the overall rate.

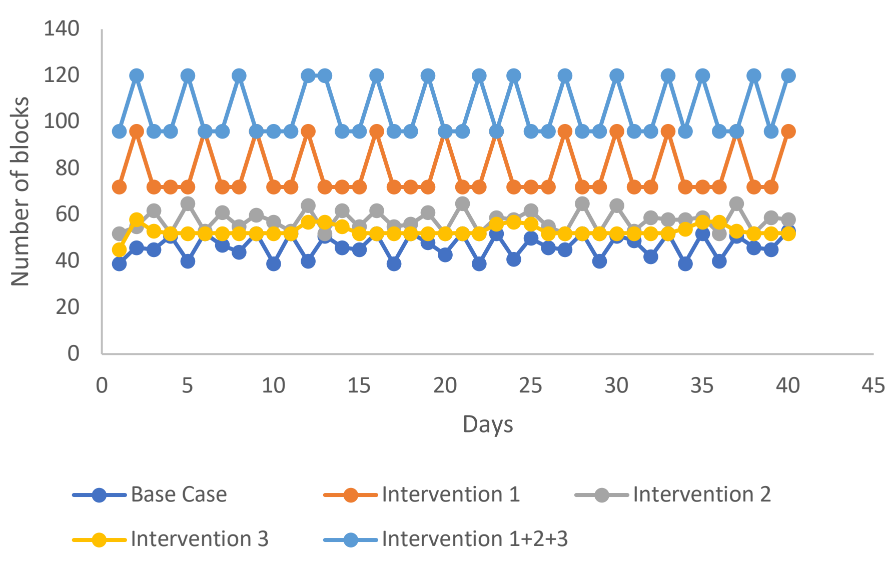

Figure 31: Average Daily Productivity

Moreover, the mean daily construction productivity rate is shown in Table 9:

	Mean	Std. Deviation	CV
Base Case	46.50	5.00	11%
Intervention 1	79.20	11.14	14%
Intervention 2	57.53	4.52	8%
Intervention 3	52.98	2.37	4%
Intervention 1+2	82.20	12.02	15%
Intervention 1+3	100.20	9.24	9%
Intervention 2+3	67.93	4.03	6%
Intervention 1+2+3	105.00	11.77	11%

Table 9:Average Daily Construction Rate

It should be noted that the variation still hovers around 10% after the interventions due to the modular nature of construction in Intervention 1; 24 blocks constituting a panel are only counted to be done on a particular day only when the entire panel is done and lifted.

8.4.3. Statistical Analysis

Ensuring that the average daily construction rates for the interventions differ is essential. To do so, it is first to identify if the different data sets obtained are normal and proceed accordingly. The data was tested using the D'Agostino-Pearson test. We get the results shown in Table 10:

Base Case	NORMAL
Intervention 1	NOT NORMAL
Intervention 2	NORMAL
Intervention 3	NOT NORMAL
Intervention 1+2	NOT NORMAL
Intervention 1+3	NOT NORMAL
Intervention 2+3	NOT NORMAL
Intervention 1+2+3	NOT NORMAL

Table 10:Data Distribution

Such results are expected due to the nature of Interventions 1 and 3. Intervention 1 shows the number of blocks laid based on the number of panels done. Hence, the total number may vary in increments of 24 blocks. As for Intervention 3, the nature of the system makes the process very regularized, with minimal variation in the time taken to lay one block.

Since the data is not normal, it is essential to use a two-tailed Wilcoxon Unpaired Rank Sum Test (nonparametric unpaired t-test) to test whether the means of the different interventions are truly different. If they are different, the interventions actually affect construction time and positively impact masonry construction. Alpha (the significance level) was set to 0.05. The interventions were compared with the base case and with each other.

The two hypotheses are shown in equations 5 and 6:

Equation 5: H_0 t-test

$$H_0: \mu_{Group\ 1} = \mu_{Group\ 2}$$

Equation 6:H_a t-test

$$H_a: \mu_{Group\ 1} \neq \mu_{Group\ 2}$$

If we reject H_0, the interventions would be different, and the results obtained are significant. Table 11 shows the results of the t-test.

Pair	Decision
Base Case VS Intervention 1	Reject H_0
Base Case VS Intervention 2	Reject H_0
Intervention 1 VS Intervention 2	Reject H_0
Base Case VS Intervention 3	Reject H_0
Intervention 1 VS Intervention 3	Reject H_0
Intervention 2 VS Intervention 3	Reject H_0
Base Case VS Intervention 1+2	Reject H_0
Intervention 1 VS Intervention 1+2	Do Not Reject H_0
Intervention 2 VS Intervention 1+2	Reject H_0
Intervention 3 VS Intervention 1+2	Reject H_0
Base Case VS Intervention 1+3	Reject H_0
Intervention 1 VS Intervention 1+3	Reject H_0
Intervention 2 VS Intervention 1+3	Reject H_0
Intervention 3 VS Intervention 1+3	Reject H_0
Intervention 1+2 VS Intervention 1+3	Reject H_0
Base Case VS Intervention 2+3	Reject H_0
Intervention 1 VS Intervention 2+3	Reject H_0
Intervention 2 VS Intervention 2+3	Reject H_0
Intervention 3 VS Intervention 2+3	Reject H_0
Intervention 1+2 VS Intervention 2+3	Reject H_0
Intervention 1+3 VS Intervention 2+3	Reject H_0
Base Case VS Intervention 1+2+3	Reject H_0
Intervention 1 VS Intervention 1+2+3	Reject H_0
Intervention 2 VS Intervention 1+2+3	Reject H_0
Intervention 3 VS Intervention 1+2+3	Reject H_0
Intervention 1+2 VS Intervention 1+2+3	Reject H_0
Intervention 1+3 VS Intervention 1+2+3	Do Not Reject H_0
Intervention 2+3 VS Intervention 1+2+3	Reject H_0

Table 11:T-test Results

We can see that in only 2 cases utilizing the improvements does not lead to a significant difference in construction time. The two cases are as follows:

- Intervention 1 and Intervention 1+2: The use of the interlocking CMU block did not affect the total construction time since the mortar is mixed by the modular unit rather than at a distance. Hence, the time it takes to handle the mortar for one CMU block does not significantly affect the total daily construction time. In other words, using mortar has little impact on the total duration of construction when dealing with modular construction.

- Intervention 1+3 and Intervention 1+2+3: The results obtained with and without the use of the interlocking CMU block are not statistically different regarding the daily construction time due to the modular nature of construction in both these scenarios.

However, it is important to note that while time was the main factor considered when comparing, the use of the interlocking CMU block allows for saving on mortar and would hence reduce the amount of money spent on material procurement. Moreover, the absence of mortar allows workers to do less strenuous work as all mortar mixing and handling activities were essentially made redundant.

8.4.4. Station Utilization

The Station utilization was derived for all three interventions (and their respective combinations). The station utilization remains the same for Intervention 1, Intervention 3, and Intervention 1+3 since the traditional masonry construction process is used in these interventions. However, since the steps relating to mortar were made redundant for Intervention 2, Intervention 1+2, and Intervention 1+2+3, the standard deviation for station utilization was calculated. The wall finish is the bottleneck. However, in these interventions, the entire process comprises two rather than the five steps in traditional masonry construction. "Wall Finish," in our case, has a near 100% utilization rate, meaning that placing the blocks constitutes overall a minor part of the entire operation duration.

Moreover, the standard deviation is smaller than in the traditional masonry construction process, so we have less variation within each step. Hence, these three solutions stabilized the process and yielded an unstressed construction system. Figure 32 shows the utilization rate for each station when the masonry construction process is composed of laying the CMU block and finishing the wall subsequently. Compared to the base case scenario, the wall finish is far more uniform in duration due to the interventions that lead to a smaller standard deviation in the activity itself.

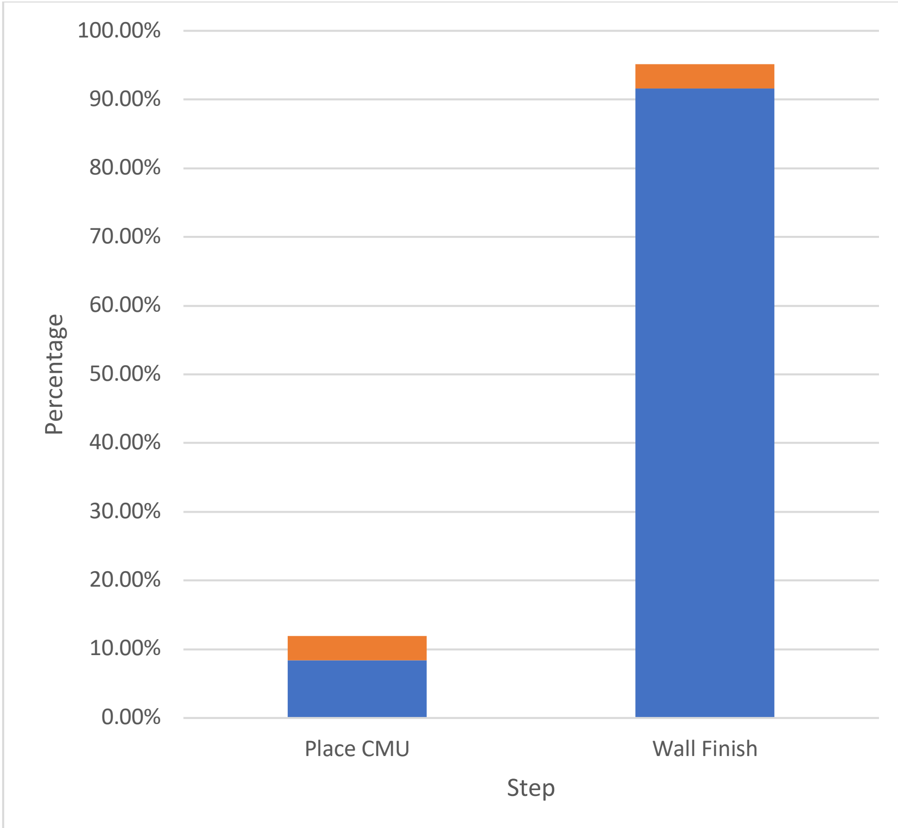

Figure 32:Station Utilization

The coefficient of variation for placing the CMU block stayed the same at 42%, while the coefficient of variation for finishing the wall decreased to 4%. While it can be argued that we see the same variability in placing the CMU block, it is important to note that the time it takes to put a CMU block depends on the many factors that were taken into consideration in this study, such as the improvement of a mason's ability to perform the masonry construction process.

8.5. Validation of Results

Based on the assumptions and data gathered, the results were obtained following the simulation of all the interventions and their respective combinations. To ensure that the results are well grounded, the models have been validated by the superintendent of the construction site, where the data about the masonry construction process was collected. The validation of the intervention was also performed by asking masonry construction industry practitioners for their input concerning the different interventions. The validation questionnaire is composed of 5 questions. The questionnaire was given with a Likert scale of 1 to 5, ranging from 5= "Strongly Agree" to 1=

“Strongly Disagree”. Table 12 shows the results of the questionnaire.

	Modular Construction	Interlocking CMU block	Robot
The solutions proposed are realistic and can be implemented.	4	2.5	3.5
The solutions proposed are logical and aim to remediate the current challenges faced in masonry construction.			
The solutions have quantitative impacts that are logical.			
The solutions proposed are significant and are considered improvements in regard to masonry construction practices.			
The results of the simulation models are logical, reasonable, and relevant.			

Table 12:Results

It was found that the use of modular construction and the robot were seen as more acceptable than the interlocking CMU block. Moreover, for the interlocking block, it was found that the complete removal of mortar may not be completely feasible, but the system of construction involving the interlocking block should include some type of mortar alternative to bond the blocks together. However, all solutions proposed, and their simulation results were found to be logical and have an impact on the masonry construction process.

8.6. Conclusion

This chapter discusses the different lean scenarios and their respective combinations. The different solutions proposed in this chapter come from the different symposiums, meetings, and multiple visits to a construction site. The simulation models developed allowed us to look at the long-term behaviour of the potential lean solutions and interventions. The interventions were simulated as stand-alone interventions but as combinations of interventions too. Intervention 1+2+3yielded the best results regarding the improvement of construction site condition since it simplifies the masonry construction process, reduces variability in the availability of material on-site, simplifies material handling, gets rid of mortar altogether, resulting in long-term gains in both productivity and cost reduction. It is important to note that several assumptions were made in this comparison. First, the different steps undertaken in the masonry construction process and their respective durations were taken from the base case scenario of masonry construction.

Moreover, different factors can also be taken into consideration when performing a comparison between the three systems and their respective combinations. The results obtained in this chapter are based on the simulation models developed, and the comparison was mainly based on the construction lead time of the different systems. If other factors are studied, the results obtained might vary. It is also important to note that the sequence of steps undertaken in the three systems is for the typical horizontal shear wall.

9. Conclusions

9.1. Thesis Summary

This thesis aimed to provide a new framework for improving construction site conditions in a masonry construction setting. The research performed is deeply rooted in lean thinking and theory applied to construction sites. It includes the application of a myriad of tools and techniques, such as Value Stream Mapping. The lean tools applied in this thesis were used along with Simulation Modelling. Simulation Modelling results were analyzed based on lean thinking with the objective of improving construction site conditions. The approach taken in this study is not only limited to application for the masonry construction process of construction but can be used and applied for any construction system and flow.

The thesis started by explaining how waste has been negatively affecting construction processes and construction site conditions and how lean thinking has been introduced to the construction field to reduce waste. The introduction of the thesis included a brief overview of the current state of masonry and the problem of simply taking one factor into account when trying to improve construction site conditions. Two research questions were hence presented to tackle the problem of waste on construction sites:

- How can masonry construction site conditions be studied to pinpoint the different areas in need of improvement?

- How can different lean tools and lean thinking be used to improve construction site conditions?

The methodology adopted in this thesis is Design Science Research which is composed of three different steps: (1) problem identification, (2) Framework Development, and (3) Framework Evaluation. The problem in current research is the targeted mitigation and improvement of some aspects or factors on a construction site rather than tackling the conditions on both macro and micro levels. There is a need to look at construction site conditions from another perspective and see how different elements, agents and resources impact the construction flow.

The artifact of the Design Science Research methodology is the framework itself. The framework aims to provide the basis for analyzing, evaluating, and improving construction site conditions. The framework was tested using a case study of the masonry construction process on a construction site. Chapter 2 introduces the framework methodology and highlights all the steps needed to evaluate current site conditions and the lean tools available for subsequent improvement. Chapter 4 details the different types of walls that were found to be most common when conducting visits to a construction site. Based on lean theory and thinking, the deltas of the different wall configurations were provided along with their pros. Chapter 4 explains how the data was collected for the case study and the case study itself.

The framework developed in this thesis puts forward two phases of the study. The first phase aims to provide the base-case scenario for a construction flow and come forward with a tool to study the current state of construction on site using Value Stream Mapping and Simulation Modelling. Chapter 6 goes into detail about the current state Value Stream Map that was developed for the masonry construction process. Chapter 6 details the steps also taken to verify and validate the map so it can be analyzed and used to identify the bottlenecks on site. Chapter 7 describes the development of the simulation model developed based on the value stream map to understand the system's long-term behaviour. The models developed allowed us to get three metrics: construction lead time, daily productivity, and station utilization. These chapters constitute the first part of the framework where the current state of construction site conditions is established.

The second phase consists of the proposed improvement with lean thinking in mind. This step is done in light of the results obtained in the previous phase. In this phase, lean interventions are presented and simulated. The different possible combinations of intervention combinations are also studied and analyzed. Chapter 8 presents the three interventions possible to improve construction site conditions: (1) Use of Modular Construction, (2) Use of an Interlocking Masonry CMU block, and (3) Use of a robot platform to help with material handling on site. The interventions all yielded different performance results when tested, both on a micro and macro level.

Results and metrics measured all concluded that implementing Interventions 1+2+3 together would constitute the most optimal solution where the construction lead time is the lowest, the daily productivity high and overall improvement of construction site conditions with the elimination of mortar as a resource, the integration of a robot platform to help with resources handling and the integration of modular construction in the construction flow. The result of the implementations is a 68% decrease in construction lead time, reduced use of materials on site, and the implementation of just-in-time delivery of materials.

9.2. Thesis Conclusions

The results obtained from the simulation models developed for the improvement of construction site conditions yielded conclusive results on the behaviour of a process and the impact lean interventions have on the flow of construction. The metrics taken, along with the observations made on the current state of construction of a site, allowed us to succeed in giving us a perspective on how the future of construction can look like. This perspective will enable us to answer the two research questions asked at the beginning of the study:

- How can construction site conditions be studied to pinpoint the different areas of improvement?

The state of a construction site can be translated into many factors that need to be analyzed and studied to understand the flow of construction on site better. This is a primordial step since lean thinking philosophy is based on identifying problems, knowing their root cause, and ensuring that the proposed solutions target the root cause of the problem and is targeting effectively. Indeed, productivity is not the only factor that needs to be considered when looking at a system's performance. Rather, it is essential to understand how all the different moving parts interact to get such productivity. Indeed, a system may have high productivity but may not be operating at an optimal state where resources may be wasted. Hence, it is necessary to ensure that the system obtained after implementing lean interventions is not full of waste and inefficiencies but rather stable with standardized work steps. To achieve such a goal, it is necessary to consider waste generation during construction (over-utilization, material inventory, equipment usage, etc.). Several interventions and intervention combinations tested provide different solutions to different problems. Intervention 2 provides a solution for the problematic use of mortar.

In contrast, Intervention 3 solves the problem of having constant back and forth between the inventory and the location on site where a wall is being erected. These findings allow us to conclude that not every solution can solve all of the on-site problems regarding waste from different perspectives. Instead, a combination of interventions is most appropriate.

- How can different lean tools and lean thinking be used to improve construction site conditions?

The tools and principles used in this study are powerful due to their mooring in lean thinking and lean philosophy. The tools and principles chosen were chosen for their reliability and known effectiveness rather than being chosen arbitrarily and haphazardly. Value Stream Mapping was done to understand the current state of the masonry construction process and identify bottlenecks in the current way of doing things. Furthermore, simulation modelling was used to evaluate and quantify different metrics, such as the construction lead time and station utilization. Combined with lean thinking and philosophy, these tools were used to improve construction site conditions. Lean thinking affirms that change and improvement cannot happen if a system is poorly understood and cannot be quantified with measured metrics and performance. Hence, using the construction lead time, among other metrics, to assess the state of the current construction practices and the proposed solutions. Using these tools with a lean thinking approach to the construction flow allowed the effective improvement of construction site conditions.

Finally, a significant conclusion to be inferred from all the work done in this study is the importance of being on a construction site to observe what is happening. It is crucial to do so and visit multiple times, as one visit may not allow us to capture the full scope of the work being done on-site and the subsequent construction flow that arises from the sum of all of the different steps and scopes Talking to people involved directly with the work being done is essential as their expertise and hands-on approach to their daily challenges provides valuable insight as to the flow of construction and potential disruptions that may come up during the process.

9.3. Study Contribution

9.3.1. Academic Contributions

The study contributes to the academic body of science. First, a framework was developed to better understand and improve construction site practices and productivity using Value Stream Mapping and Simulation Modelling. The framework was developed based on Design Science Research, and its testing was done using a case study involving a typical horizontal masonry shear wall and different masonry construction systems alternatives. Moreover, ways to improve construction site conditions using lean practices to create a semi-autonomous construction system on construction sites were suggested. The interventions tested allowed us to conclude that the best way to improve masonry construction is by testing and simulating different systems and comparing them based on predefined metrics.

9.3.2. Industry Contributions

The study's goal is to directly contribute to the betterment of the industry by changing the masonry construction practices done on construction sites. Indeed, the three systems studied aim to reduce labour, equipment, and material waste. Adopting the systems studied in this study makes it possible to cut down construction costs due to the direct impact of the practices on resource usage (mortar) and construction time perspectives. Moreover, this study defined the role of a robot on a construction site. Indeed, by dividing construction tasks between workers and a robot on construction sites, it is possible to have better handling of materials (in our case, CMU blocks) on a construction site.

In conclusion, the study's contributions presented in this thesis are multiple. First, the most common patterns of shear masonry wall configurations have been complied with and presented with their pros and deltas from a lean perspective. They form the basis for the chosen construction processes to be studied. Second, the developed framework for the improvement of construction site conditions using lean principles explains the different steps to undertake when analyzing a construction process and the construction flow. Third, the study proved that using a myriad of different tools, such as Value Stream Mapping and Event Simulation combined with lean thinking, leads to a robust analysis of construction site conditions. Fourth, the different simulation models can develop the masonry construction system's productivity independently of wall length and number of rows that need to be built. Three lean interventions were proposed and proven to positively impact construction site conditions when appropriately implemented. Finally, the results indicate that one intervention alone cannot solve all the problems related to construction site conditions. Instead, a combination of solutions targeting a specific waste area on a construction proved most effective. It is essential to look at the entire system both on a macro level and micro level to understand the effect each intervention has.

9.4. Limitations

The study performed in this thesis includes several limitations. First, the value stream map does not include the supply chain issues that may adversely affect the construction flow. While the value Stream Map has been verified and validated by masonry construction industry practitioners, including the supply chain in the map would allow for better quantification of issues that may arise and adversely affect construction site conditions. Second, the case study of masonry construction studied the typical horizontal shear wall when data was collected and did not take into consideration rework into the cycle times and overall duration of the different steps of the masonry construction process. Shapes such as L-shaped and T-shaped walls can require additional steps than the one identified for the typical horizontal shear walls in the case study. Moreover, the comparison is not considered comprehensive and includes the study of a typical horizontal shear wall for a school gymnasium only.

Furthermore, the results obtained from the simulation models only apply to the systems investigated in this study, i.e., the base case scenario for masonry construction, intervention 1, intervention 2 and intervention 3 (and their different combinations). Moreover, in the simulation models, factory physics and transfer of variability were not taken into consideration when modelling the masonry construction process. Additionally, the modelling was done with the assumption that the measurement of the metrics is done per CMU block rather than per m^2 or ft^2.

Finally, the results obtained were validated using face validity due to the nature of the results obtained. The metrics and conclusion of the pros and deltas of each lean intervention were obtained based on the simulation models rather than testing the interventions on-site.

9.5. Future Research Recommendations

The research proposed in this thesis opens the door for future research, such as the study of construction site conditions for more complex wall shapes such as L-shaped and U-shaped. This would create a new comprehensive framework where all shapes can have a standardized construction method. Moreover, it is also possible to study all the parts affecting the supply chain to understand better all the factors that may affect construction site conditions. This potential study would require collaboration with all the stakeholders of a construction project for success. It is also possible to investigate other systems than the ones studied in this thesis as well as adding more metrics and factors into the analysis. It is also possible to take more resources into consideration and look at the usage of resources in terms of volume (for mortar), for example. Moreover, it is also possible to study the process per m^2 or ft^2 for metrics measurements. Additionally, it is also possible to take into consideration factory physics and transfer of variability when developing the simulation models. It is also possible to perform the data collection using computer vision to make a better analysis.

On another note, is it possible to research the integration of design as a component to study concurrently with construction. Indeed, it would allow us to know where the design can change in pre-construction phases to identify potential problems that may arise during construction and change the design accordingly. Finally, integrating Lean Construction 4.0 into the current construction flow practices may further improve construction site conditions. This addition will allow us to look at the impact of construction on different levels, such as legal and social aspects. These will need to be included in future sustainable, technologically innovative solutions to reduce waste and variability, increase value, and ultimately contribute to better management of construction site conditions.

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