T.C.

İSTANBUL KÜLTÜR UNIVERSITY

INSTITUTE OF GRADUATE STUDIES

# ASSESSING THE EFFECT OF LEAN TECHNIQUES ON CONSTRUCTION PROJECTS PERFORMANCE

**Shehabeddien ELORABY**

**1800005658**

**Department: Industrial Engineering**

**Program: Engineering Management**

**Supervisor: Assist. Prof Dr. Okay IŞIK**

**FEBRUARY 2024**

**T.C.**
**İSTANBUL KÜLTÜR UNIVERSITY**
**INSTITUTE OF GRADUATE STUDIES**

# ASSESSING THE EFFECT OF LEAN TECHNIQUES ON CONSTRUCTION PROJECTS PERFORMANCE

**Shehabeddien ELORABY**

**1800005658**

**Department: Industrial Engineering**

**Program: Engineering Management**

**Supervisor: Assist. Prof Dr. Okay IŞIK**

**Members of Examining Committee:**

**Assist. Prof. Erdal Coşkun**

**Assist. Prof. Eylül Sezer**

**FEBRUARY 2024**

# ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my thesis advisor, Okay IŞIK. Your guidance, expertise, and unwavering support throughout this research journey have been invaluable. Your insightful feedback and constant encouragement provided me with the confidence and direction to pursue my research ambitions. I am truly grateful for your mentorship and dedication to my academic development.

Beyond academia, I owe a tremendous debt of gratitude to my loving parents. Your unwavering belief in me, along with your unwavering support and sacrifices, have been the bedrock of my achievements. Words cannot express my gratitude for the countless hours you spent nurturing my curiosity, fostering my love for learning, and motivating me to reach for my goals. Thank you for always being my biggest cheerleaders.

To my beloved wife, thank you for sharing this adventure with me. Your unwavering love, unwavering support, and understanding have been the fuel that kept me going during times of challenge. You were my confidante, my voice of reason, and my rock of support. This thesis would not have been possible without your love and encouragement.

Last but not least, I would like to thank my most dear siblings, thank you for your constant love, laughter, and encouragement. Your unwavering belief in me and your willingness to listen and offer support have been a source of strength and solace throughout this journey. I am truly blessed to have such a supportive family by my side.

From the bottom of my heart, thank you all for your love, support, and inspiration. This thesis is a testament to your unwavering belief in me.

| Date | Name SURNAME |
|---|---|
| 20/01/2024 | Shehabeddien ELORABY |

# TABLE OF CONTENTS

## LIST OF TABLES

# LIST OF FIGURES

**Üniversite** : **İstanbul Kültür Üniversitesi**
**Enstitü** : **Lisansüstü Eğitim Enstitüsü**
**Anabilim Dalı** : **Endüstri Mühendisliği**
**Programı** : **Mühendislik Yönetimi**
**Tez Danışmanı** : **Dr. Öğretim Üyesi OKAY IŞIK**
**Tez Türü ve Tarihi** : **Yüksek Lisans – Şubat 2024**

# ÖZET

## Yalın Tekniklerin İnşaat Projeleri Performansına Etkisinin Değerlendirilmesi

**Shehabeddien ELORABY**

Verimsizlik ve israfın inşaat sektörüne nüfuz etmesi; proje sürelerinin uzaması, şişirilmiş maliyetler ve kaynak kullanımının optimuma ulaşamaması şeklinde kendini göstermektedir. Ancak, yalın inşaat ilkeleri umut vadeden bir paradigma değişimi sunarak, süreçlerin daha akıcı hale gelmesini ve verimliliğin artırılmasını mümkün kılmaktadır. Bu araştırma, önemli bir soruyu ele almaktadır: Yalın araçlar, geleneksel yöntemlere kıyasla inşaat verimliliğini, üretkenliği ve performansını hangi ölçüde artmasını sağlayabilir? Titiz bir simülasyon modelleme yaklaşımını benimseyen bu çalışmada, hem temel (geleneksel) hem de yalın senaryoları içeren kapsamlı modeller geliştirmek için ARENA 16.2 yazılımı kullanılmıştır. Bu modellerin titiz bir şekilde karşılaştırılmasıyla, yalın tekniklerinin entegre edilmesinin etkinliği konusunda istatistiksel olarak anlamlı içgörüler elde edilmiştir. Bulgular, yalın tekniklerin proje sonuçlarının iyileştirmesindeki dönüştürücü gücüne dair ikna edici kanıtlar sunmaktadır. Değer belirleme, değer akışı haritalama, değer akışı, çekme üretimi ve sürekli iyileştirme gibi temel ilkelerin uygulanması, performansta önemli kazançlar sağlamıştır. Ayrıca, süreç ve operasyonel yönlerin optimizasyonu, proje toplam süresini daha da kısaltarak, yalın yaklaşımın faydalarını güçlendirmiştir. Modeller, istinat duvarı inşaat süreci için %7.79 verimlilik artışı ve döngü süresinde %30.29'lik bir azalma göstermiştir. Kısacası, bu araştırma, yalın araçların uygulanmasının ölçülebilir etkisini nicelleştirerek, inşaat uygulayıcılarına net kanıtlar sunarak ve yalın düşüncenin yerleşik yönetim yaklaşımlarına sorunsuz şekilde entegre edilmesi için pratik kılavuzlar geliştirerek, potansiyel gösteriminin ötesine geçmektedir. Bu çalışma, teori ile pratik arasındaki boşluğu kapatmakta ve yalın inşaatın dönüştürücü gücünü kanıtlamaktadır.

**Anahtar Kelimeler:** Yalın İnşaat, Ayrık Olay Simülasyonu, Atık azaltma, Performans Geliştirme, ARENA

**Bilim Dalı Sayısal Kodu:** 90602

| | |
|---|---|
| **University** | **: İstanbul Kültür University** |
| **Institute** | **: Institute of Graduate Studies** |
| **Department** | **: Industrial Engineering** |
| **Program** | **: Engineering Management** |
| **Supervisor** | **: Assist. Prof. OKAY IŞIK** |
| **Degree Awarded and Date** | **: MS – February 2024** |


## ABSTRACT

## Assessing the Effect of Lean Techniques on Construction Projects Performance

**Shehabeddien ELORABY**

Inefficiency and waste permeate the construction industry, manifesting as extended timelines, inflated costs, and suboptimal resource utilization. Lean construction principles, however, offer a promising paradigm shift, enabling process streamlining and enhanced productivity. This research delves into a crucial question: to what extent can lean tools demonstrably improve construction efficiency, productivity, and performance compared to traditional methods? By adopting a rigorous simulation modeling approach, this study utilizes Discrete Event Simulation Approach to develop comprehensive models encompassing both baseline (conventional) and lean scenarios. By meticulously comparing these models, statistically significant insights were generated into the effectiveness of integrating lean techniques. The findings provide compelling evidence for the transformative power of Lean in improving project outcomes. Applying key principles like value specification, value stream mapping, value flow, pull production, and continuous improvement resulted in significant performance gains, while optimizing process and operational aspects further reduced project total time, solidifying the benefits of a leaner approach. Lean models demonstrated a 7.79% increase in process efficiency and a 30.29% reduction in cycle time for the retaining wall construction process, Moreover, the research

transcends mere potential demonstration by quantifying the measurable impact of implementing specific lean tools, providing construction practitioners with clear evidence of their effectiveness, and developing practical guidelines for seamlessly integrating lean thinking into established management approaches, bridging the gap between theory and practice.

**Keywords:** Lean Construction, Discrete Event Simulation, Waste reduction, Performance Improvement, ARENA

**Science Code:** 90602

# 1. INTRODUCTION

## 1.1. Background Information:

The global construction industry is beset by a multitude of challenges. Project cost overruns, schedule delays, and scope creep are hallmarks of the sector, leading to concerns about project effectiveness and efficiency. Issues such as delays, overspending, and compromised quality remain prevalent, despite the continued application of conventional construction management techniques. While some successes have been achieved using these traditional methods, the industry's persistent struggles necessitate the exploration of alternative approaches. The reliance on conventional activity-based project management methods in construction, where task sequencing is dictated by the critical path approach, often necessitates prioritizing tasks to mitigate potential delays. This can lead to decisions to reschedule tasks and redeploy personnel, which in turn can negatively impact overall project performance and productivity (Koskela, Howell, Ballard, & Tommelein, 2002). Within the construction industry, project management often adheres to a transformational paradigm, prioritizing the conversion of inputs into value-generating outputs. This perspective implicitly links total project cost to the nature and quantity of these inputs, leading managers to primarily focus on optimizing input variables. Consequently, essential flow principles and concepts inherent in effective production systems tend to be overlooked. This neglect manifests in the construction process as significant waste generation and value loss, indicating potential inefficiencies in the underlying management approach (Abdel-Razek, Abd Elshakour M, & Abdel-Hamid, 2007). Despite ongoing efforts to modernize conventional project management methodologies, their efficacy has been significantly undermined by the evolving nature of project contexts. Empirical studies have revealed the inadequacy of traditional approaches in addressing the complexities and challenges of contemporary projects. (Rebaiaia & Vieira, 2014). Furthermore, stagnating performance has been identified as a significant challenge within the construction sector, documented in prominent industry review reports and recent policy initiatives. This necessitates a dual approach that simultaneously incorporates waste identification and reduction strategies alongside value-adding initiatives. Through such co-implementation, opportunities for performance improvement can be effectively addressed.

### 1.2. Aim of the research:

The construction industry is plagued by pervasive issues of inefficiency and waste, leading to prolonged project timelines, increased costs, and suboptimal resource utilization. However, the potential for streamlining processes and enhancing productivity is offered by lean construction principles. In this research, a rigorous simulation modeling approach is employed to delve into the potential impact of integrating lean principles into a specific construction process. A baseline model meticulously constructed to replicate the current state serves as a benchmark for comparison. Subsequent iterations incorporating lean principles will be compared against this baseline, allowing for a quantitative assessment of their effectiveness in improving efficiency and reducing waste. Ultimately, this research aims to provide empirical evidence for the transformative potential of lean construction, paving the way for industry-wide performance improvements.

#### 1.2.1. .. Primary Objective:

Motivated by the persistent challenges of inefficiency and waste in construction, this research assesses the potential of lean tools and techniques to fill a critical gap in optimizing performance. It specifically focuses on achieving this by enhancing efficiency, and overall effectiveness, with a primary emphasis on eliminating time-related waste and reducing project duration.

#### 1.2.2. .. Secondary Objectives:

*Baseline Model Development:*

- Construct a comprehensive baseline model accurately replicating the current state of the chosen construction process.
- Identify and categorize potential waste types for each activity within the process.
- Develop a detailed process map outlining the sequence of activities.

- ... Assign sub-activity durations using a Triangular Probability Density Function, informed by real-world observations and expert opinions.
- ... Utilize Discrete Event Simulation (DES) approach with ARENA 16.2 software to simulate the baseline model, reflecting the "real-world" scenario.
- ... Validate the model results against real-world observations or historical data collected from the construction process.

*Lean Implementation to Case Study Activities*

- ... Theoretically Implement specific Lean techniques and tools into non-lean case study to obtain a Lean scenario.
- ... Assign sub-activity durations using a Triangular Probability Density Function, informed by expert opinions based on site unique conditions.
- ... Comparative analysis with the non-lean scenario, highlighting the potential performance improvements enabled by Lean principles.

*Lean Construction Model Development:*

- ... Formulate and incorporate specific lean construction principles tailored to address identified wastes in the baseline model.
- ... Develop a "lean construction" scenario model reflecting the application of these principles.
- ... Ensure comparability between the baseline and lean construction models by maintaining equivalent scope and initial conditions.

*Comparative Analysis:*

- ... Run simulations for both the baseline and lean construction models under identical conditions.
- ... Analyze key performance indicators such as cycle time, lead time, resource utilization, and waste reduction in both models.
- ... Quantify the potential improvements in efficiency and productivity achieved through the implementation of lean principles.

*Limitation and Generalizability:*

- ... Discuss the limitations and generalizability of the findings to other construction contexts and project types.

### 1.3. Thesis Question

This thesis provides an answer to the following question:

Q: To what extent can lean tools deliver measurable gains in construction efficiency, productivity, and performance compared to traditional methods?

Answering this question can clarify the potential significant influence of implementing lean techniques to reduce waste, non-value adding activities, and overall project duration, improving the performance of construction projects.

### 1.4. Research Contribution:

Conventional project management approaches in construction companies often suffer from control and monitoring deficiencies, leading to a reactive rather than proactive strategy. This results in measures being primarily implemented after issues arise, leaving little room for preventive intervention. To address this, alternative proactive approaches like Lean Construction offer promising potential. Lean Construction, however, remains underutilized in Saudi Arabia, despite its effectiveness demonstrated in projects outside the region. Moreover, the existing Lean Construction literature predominantly focuses on data acquired from non-Saudi contexts, leaving a gap in understanding its applicability and impact within Saudi Arabia's unique construction environment. This research fills this crucial gap by investigating the application of Lean principles to a specific Saudi construction project, offering valuable insights into its potential for optimizing performance and overcoming the limitations of traditional approaches.

### 1.5. Scope and structure of thesis (Essay map):

This research investigates the potential benefits of integrating Lean techniques into traditional construction project management. Specifically, it focuses on measuring performance improvement during the crucial monitoring and control phase.

### 1.5.1. .. Approach:

*Simulation Modeling:* A rigorous simulation model will be developed, meticulously reflecting the current state of a specific construction process. This baseline model acts as a benchmark for comparison.

*Lean Integration:* Successive iterations of the model will incorporate various Lean principles. By comparing these against the baseline, we can quantify the effectiveness of Lean in enhancing efficiency and minimizing waste.

### 1.5.2. .. Thesis Structure:

- **Introduction:** Provides context, outlines research objectives, defines the research question, and highlights the study's significance and scope.
- **Literature Review:** Explores the concept of Lean construction, its proven benefits, and relevant prior research. A critical comparison of existing studies is offered.
- **Methodology:** Details the framework development employed to achieve the research goals. This includes simulation model construction, Lean principal selection, and performance measurement strategies.
- **Implementation and Results:** Presents the chosen case study, describes the implementation process, and analyzes the obtained results. Specific improvements arising from Lean integration are identified and quantified.
- **Conclusion:** Summarizes the research findings, presents key recommendations for Lean implementation (including actionable data and insights).

# 2 LITERATURE REVIEW

## 2.1. Lean Management

Derived from Toyota Production System (TPS), the lean production idea was first developed and introduced as a theory in Japan by Taiichi Ohno (Ohno, 1988) (Chiarini, Baccarani, & Mascherpa, 2018). Meeting the customer expectations by continuous improvement is the main idea of lean management, as it consists of a set of methods and practices that aim to eliminate all non-value-adding activities and wastes to attain high productivity and quality with more flexible production (Bilagi & Vasanthakumara, 2017) (Mostafa, Dumrak, & Soltan, 2013). However, the term "lean" was developed by experts studying global auto production to describe the Toyota production system's waste reduction features in contrast to more conventional mass-production methods (Womack J. J., 1991). (Womack & Jones, 1996) argued that lean thinking could benefit companies: “specify value, line up value creating actions in the best sequence, conduct these activities without interruption whenever someone requests them, and perform them more and more effectively.” (Figure 2-1) (Womack & Jones, 1996). Thus, five main principles of lean thinking could be extracted from the above statement:

- **Value specification**

Meeting the necessary requirements and providing the customer with the intended value are crucial. Customer value becomes the shared focus for all stakeholders participating in the project when value for the product or service is clearly defined.

- **Value stream identification**

The whole processes are necessary to supply a service or product, followed by an evaluation of how well the customer value is being provided. This reflects the complete process that provides value to the customer and necessitates the elimination of any non-adding value activity (Swefie, 2021). Eliminate any procedures or actions that do not enhance or add value to the final product to identify the value stream. This indicates that once a process or a product has a problem, it should be stopped and changed or fixed right away. Overproduction, superfluous inventories, labor mobility, transit of materials and goods, necessary production of materials or products not in accordance with customer needs and requests, and unnecessary waiting times are generally the activities or processes that must be avoided (Aziz & Hafez, 2013).

- **Non-interrupted product flow**

By obtaining the optimal workflow, the workflow may be maintained. A suitable workflow that ensures continuous delivery of the product or service along the entire value chain would concurrently reduce waste and boost customer value (Swefie, 2021) . Thus, by concentrating on the complete supply chain, it is necessary to ensure that the process flow is continuous, i.e., sequencing of process activities is ongoing with no stopping or break in supply chain. The objective should remain to execute a continuous process along the entire supply chain, reduce waste production, boost end-product value, or obtain value that complies with customer requirements or specifications (Aziz & Hafez, 2013).

- **Pulling value**

Producing in line with or according to client demand means meeting customer needs (Swefie, 2021). Moreover, it refers to delivering the goods when and how the consumer demands. Employ the idea of pull rather than push in the production and building processes. The fundamental goal of pull production is to limit the quantity of waste output by reducing needless production and inventories. To prevent overproduction in pull production, the management solution "Just-in-time" (JIT) is utilized (Aziz & Hafez, 2013).

- **Seeking perfection**

To constantly strive for perfection through process improvement and the application of relevant methods. The goal of the production process' continuous improvement strategy is too perfect both the process and the final product. It involves delivering a product to the customer in accordance with his or her expectations and requirements, on time, and without any flaws or errors. Maintaining regular contact with customers, managers, and employees involved in the process is the only way to attain perfection (Aziz & Hafez, 2013).

Consequently, lean management practices implementation eliminates eight types of wastes processing as shown in (Figure 2-2) (Kadarova & Demeckoa, 2016):

- ... Defects.
- ... Over-production.
- ... Waiting.
- ... Unused talent.
- ... Transportation.
- ... Inventory.
- ... Motion.
- ... Extra processing.

However, lean practices are not only adopted by manufacturing industry but also by many various industries that seek to identify and reduce wastes to improve the overall efficiency of different processes (Makwana & Patange, 2021).

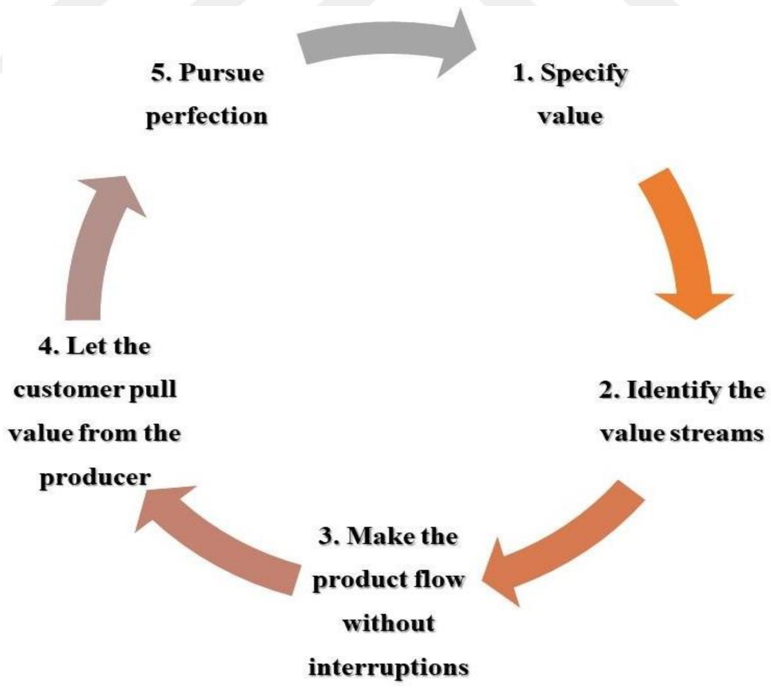



**Figure 2-1:** Lean Thinking Principles. (Abbasian-Hosseini, Nikakhtar, & Ghoddousi, 2014)

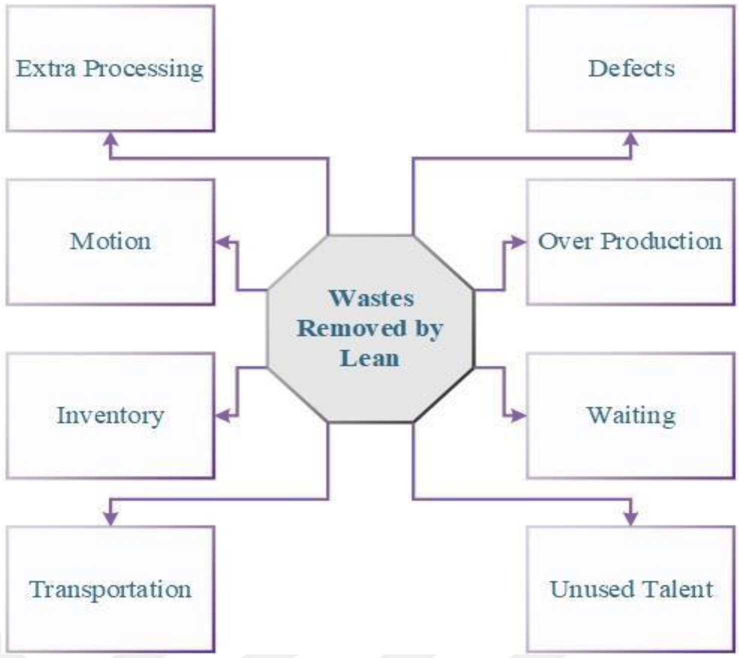



**Figure 2-2:** Types of Waste Removed by Lean. (Kadarova & Demeckoa, 2016)

### 2.2. From Lean Manufacturing to Lean Construction

Based on implementing principles and practices of lean management into construction industry, lean construction concept was developed to maximize provided value and minimize wastes in the process of construction project delivery (Ogunbiyi, Oladapo, & Goulding, 2014). Recent years have seen extensive investigation into the work on maximizing value and minimizing or eliminating wastes, which covers the application of lean production practices and concepts in the construction processes to maximize value and remove wastes (Aziz & Hafez, 2013). Lean construction is defined by (Issa H. , 2013) as a strategy of management that provides continuous improvement to the process by eliminating different wastes that do not provide adding value to the final product or service delivered to the customer. Unlike the traditional management which focuses on tasks and activities but ignores maximization of value and reduction of wastes, the lean construction approach considers the main three goals: transformation, flow, and value adding (Koskela, Howell, Ballard, & Tommelein, 2002). Thus, the primary objective of considering a project as a production system in the construction sector is to modify working methods in design and construction to enhance performance. Furthermore, the amount of waste that is typically produced during a project is the primary factor affecting the productivity of the construction sector. However, the adoption of LC can enhance the project's overall performance as well as the whole industry by ensuring that projects are delivered on time, with the proper quality and quantity of resources, and within the allocated budget. Thus, the most important advantages of using LC on a project are the decreased waste, increased value, and reduced project life cycle cost (Oguntona, Aigbavboa, & Mulongo, 2019).

### 2.3. Lean Beyond Conventional Projects Management Defections

Construction Industry is immensely complicated and needs strict procedures to accomplish projects according to schedule, efficiently, and effectively. Moreover, vast construction projects frequently experience time and financial overruns. Consequently, completing a construction project on schedule and within budget, despite its size or complexity, is the prime requisite for success. (Swefie, 2021) applying the conventional methods to management of construction projects based on activities, scheduling its sequence according to critical path method requires pursuing them to avoid delays threats. Consequently, decisions of shifting tasks and relocating workers are made, which reduces the performance and productivity (Koskela, Howell, Ballard, & Tommelein, 2002). Moreover, the construction process is managed according to a transformation view that converts inputs to outputs with value, where the total cost depends on these inputs; thus, managers focus on the inputs, neglecting principles and concepts of flow and generating value. Hence, the construction process has considerable waste and value loss (Koskela L. , 2000) (Abdel-Razek, Abd Elshakour M, & Abdel-Hamid, 2007). In contrast, it has been proved by several studies that implementation of lean philosophy principles which illustrated in (Figure 2-1) has significant potential enhancement to the construction process, which compensates these insufficiencies (Abbasian-Hosseini, Nikakhtar, & Ghoddousi, 2014). However, while tracing literature to identify the potential improvements by implementation of lean principles, a significant number of benefits that could enhance construction processes has been monitored, collected, and put in alphabetical order, as shown in (Table 2-1).

**Table 2-1** Benefits of Lean Construction.

| No. | Lean Construction Benefit | Reference |
|---|---|---|
| 1 | Cost reduction | 1, 3, 6, 9, 13, 15, 20 |
| 2 | Environmental impact and wastes reduction | 1, 3, 4, 12, 13, 19 |
| 3 | Health and safety conditions Improvement | 4, 10, 12, 18 |
| 4 | Management and control improvement | 8, 19 |
| 5 | Project waiting/total duration reduction | 2, 3, 4, 5, 6, 11, 12, 20, 21 |
| 6 | Quality improvement | 12, 15, 21 |
| 7 | Workflow, productivity, and efficiency improvement | 7, 14,16, 17, 21 |
| 1. (Arleroth & Kristensson, 2011), 2. (Garrett & Lee, 2011), 3. (Adamu & Howell, 2012), 4. (Nahmens & Ikuma, 2012), 5. (Issa H. , 2013), 6. (Tserng, Yin, & Ngo, 2013), 7. (Erol, Dikmen, & Birgonul, 2017), 8. (Abbasian-Hosseini, Nikakhtar, & Ghoddousi, 2014), 9. (AlSehaimi, Fazenda, & Koskela, 2014), 10. (Nowotarskia, Paslawskia, & Matyjaa, 2016), 11. (Bajjou, Anas, & Ennadi, 2017), 12. (Bajjou & Chafi, 2018), 13. (El-Sawalhi, Jaber, & Al Shukri, 2018), 14. (NOWOTARSKI & PASŁAWSKI, 2018), 15. (Martinez, Reid, & Tommelein, 2019). 16. (Wu, Zhao, Ma, & Yang, 2019), 17. (Bajjou & Chafi, 2020), 18. (Demirkesen, 2020), 19. (Issa & Alqurashi, 2020), 20. (Norona & Mendoza, 2020), 21. (Xing, Hao, Qian, Tam, & Sikora, 2021) | | |

### 2.4. Waste Reduction

Inefficient systems and processes within construction projects are demonstrably linked to significant waste in the form of excessive time and cost overruns. Reported estimations of construction waste reach as high as 50%, attributed to inefficiencies across all project phases, from design and mobilization through execution and maintenance (O'Connor & Swain, 2013).

The primary obstacle in minimizing construction waste lies in establishing a robust methodology for its initial identification within projects. Waste elimination efforts should be prioritized during the design phase, necessitating a clear understanding of waste types present throughout the construction process. Literature has identified eight distinct waste categories (Garrett & Lee, 2011) , as detailed below:

- ... Over/Under Production.

- ... Waiting.
- ... Unnecessary Transportation.
- ... Over/Under Processing.
- ... Excess Inventory.
- ... Unnecessary Motion.
- ... Defects.
- ... Unused Creativity of Team Members.

### 2.5. Tools and Techniques of Lean Construction

The construction industry possesses a vast arsenal of Lean tools and techniques capable of enhancing performance and streamlining processes throughout the project lifecycle, from pre-construction and construction to maintenance. (Table 2-2) provides a comprehensive overview of such tools and techniques as documented in the literature (Salem, Solomon, Genaidy, & Minkarah, 2006) and (Shehata & El-Gohary, 2011). The subsequent section presents a focused overview of key Lean tools and techniques:

#### 2.5.1. .. Identifying value components and mapping the value stream

Value, ultimately reflected in the finished product, lies at the heart of lean construction philosophy. This lens for analyzing workflows categorizes activities as either value-adding (VA) or non-value-adding (NVA). Whereas NVA activities contribute nothing to the final product's economic worth, VA activities directly impact its production and are deemed valuable by the customer. (Koskela L. , 1993) further subdivides construction activities into conversion and flow activities. Conversion activities transform raw materials and information into the final product, while flow activities, encompassing aspects like inspection, waiting, and movement, simply bridge the gaps between conversions. Though both types require time and resources, only conversions inherently generate value for the product (Koskela L. , 1993). This distinction allows us to recognize conversion activities as VA and flow activities as NVA.

Lean construction strives to achieve two key goals through process redesign:

- Minimize or eliminate the proportion of NVA activities. This can involve reducing unnecessary waiting times, streamlining material handling, and eliminating redundant inspections.
- Maximize the portion of time workers spend on VA activities. This might involve optimizing workflows, empowering teams, and implementing tools that enhance conversion efficiency.

The flow view of construction processes, inherent to lean thinking, facilitates easier identification of VA and NVA activities by revealing opportunities to increase the value delivered to the customer. This emphasis on value optimization distinguishes lean construction and serves as its core driving force (Abbasian-Hosseini, Nikakhtar, & Ghoddousi, 2014).

### 2.5.2. .. Flow as the Key to Efficiency

Lean construction reimagines production as a seamless flow of materials, information, equipment, and labor, transforming raw inputs into the finished product with minimal disruption (Yong-Woo & Jinwoo, 2010). This emphasis on stable flow, a cornerstone of lean thinking (Sacks, Treckmann, & Rozenfeld, Visualization of Work Flow to Support Lean Construction, 2009), necessitates a multi-pronged approach to optimize processes and minimize waste.

Several core techniques contribute to this goal. Reducing process variability lies at the heart of smooth workflows. Lean principles advocate for preventing defects at their source, rather than allowing them to propagate through subsequent stages. While fail-safe devices excel in automated manufacturing construction's inherent complexity demands a broader approach (Salem, Solomon, Genaidy, & Minkarah, 2006),. Here, implementing failsafe actions across all on-site activities becomes crucial. This can be achieved through comprehensive quality assessments and safety protocols established at project initiation (Salem, Solomon, Genaidy, & Minkarah, 2006).

Shortening cycle times further enhances flow. As variability decreases, so does the time required for individual tasks, leading to streamlined processes. However, achieving this reduction typically involves a collaborative effort to redesign the process for increased flexibility and efficiency (Sacks, Koskela, Dave, & Owen, 2010).

Minimizing batch sizes also plays a crucial role in optimizing workflow and reducing cycle times (Sacks, Koskela, Dave, & Owen, 2010). Smaller batches not only allow for quicker adjustments but also reduce the amount of work in progress, minimizing bottlenecks and delays.

Finally, enhancing flexibility empowers teams to adapt to changing demands and unforeseen circumstances. Techniques like quick changeovers between tasks and fostering multi-skilled teams significantly improve responsiveness and productivity (O'Connor & Swain, 2013) (Sacks, Koskela, Dave, & Owen, 2010). By equipping teams with diverse skillsets and streamlining transition times, lean construction empowers project teams to navigate challenges and maintain optimal workflow.

### 2.5.3. .. Pull Scheduling and Collaborative Planning in Lean Construction

A cornerstone of lean construction philosophy is the pull approach, a production method centered around minimizing work-in-progress inventory and only producing what is immediately required by downstream processes (Sacks, Treckmann, & Rozenfeld, Visualization of Work Flow to Support Lean Construction, 2009) . This demand-driven workflow minimizes waste and enhances efficiency by eliminating unnecessary production and stockpiling. Within the pull framework, pull scheduling emerges as a crucial technique for improving construction project flow (Thomas, Horman, Minchin, & Chen, 2003). Supporting this pull philosophy, the Last Planner System (LPS) emerges as a powerful tool for enhancing predictability and reliability. By implementing look-ahead scheduling and fostering collaborative planning between site management and trade foremen, LPS nips potential issues in the bud, preventing disruptions and delays before they materialize (Mossman, 2012). This proactive approach smooths workflows and injects greater certainty into construction projects.

Further amplifying the pull principle, Just-in-Time (JIT) production aligns material deliveries and task execution with precise customer demand, minimizing inventory requirements and optimizing equipment utilization (Morgan & Coci, 2012). This demand-responsive approach not only reduces waste but also enhances overall project efficiency.

Moving beyond individual techniques, lean construction advocates for collaborative planning, a powerful technique that brings together all project stakeholders to co-create a detailed and agreed-upon target program (Dave, Koskela, Kiviniemi, & Tzortzopoulos, 2013). Encompassing high-level and detailed scheduling, short-term production plans, daily briefings, and weekly production control, fosters clear communication and coordinated execution, further streamlining workflows, and minimizing inefficiencies. One effective method for enabling collaborative planning is Integrated Project Delivery (IPD). Defined by the AIA as a process that leverages the collective talents and insights of everyone involved to optimize efficiency throughout the project lifecycle (Dave, Koskela, Kiviniemi, & Tzortzopoulos, 2013), IPD emphasizes early stakeholder involvement, facilitated by technology and risk-sharing agreements. This fosters a collaborative environment conducive to streamlined workflows and improved resource utilization.

The adoption of pull scheduling, collaborative planning, and other lean construction principles offers substantial potential for construction projects. By minimizing waste, enhancing efficiency, and increasing project certainty, these demand-driven techniques represent a fundamental step towards maximizing project success in the dynamic construction environment.

### 2.5.4. .. Continues Improvement in Lean Construction

Lean construction's emphasis on continuous improvement provides a powerful tool for optimizing project outcomes. All lean techniques inherently support this principle, aiming to reduce variability and enhance workflow (Sacks, Koskela, Dave, & Owen, 2010). This continuous improvement can be categorized into two distinct types: process improvement and operation improvement (O'Connor & Swain, 2013).

Process improvement focuses on establishing efficient methods for project delivery, streamlining the overall process, and reducing lead time. Key benefits include enhanced work productivity, clarified roles and responsibilities, waste minimization, and lead time reduction (O'Connor & Swain, 2013) This approach primarily utilizes two methods: current state mapping (CSM) and future state mapping (FSM). CSM creates a visual representation of the existing project process, highlighting existing delays, disruptions, and waste. FSM then envisions a future process incorporating appropriate lean techniques for efficient workflow (O'Connor & Swain, 2013).

Operation improvement, on the other hand, delves into optimizing individual work activity execution. Its primary goals are reducing cycle time for completing tasks, boosting productivity, achieving "right-first time" quality, and ensuring safe working practices. This is achieved by eliminating non-value-adding activities, closely monitoring, and controlling performance, and optimizing resource allocation (O'Connor & Swain, 2013). Performance control involves setting clear metrics for quality, time, cost, and safety to guide and adjust the process throughout the project lifecycle.

By strategically pursuing both process and operation improvement, lean construction unlocks significant enhancements in project efficiency, waste reduction, and ultimately, project success.

### 2.5.5. .. Transparency through the 5S' and Visualization in Lean Construction

A cornerstone of lean construction is transparency, fostering clear communication and efficient workflow. One impactful tool in achieving this is the 5S methodology, initially developed in manufacturing (Salem, Solomon, Genaidy, & Minkarah, 2006). Thus, applying the 5S's in construction promotes a transparent job site, enabling smooth material flow from warehouses to work areas. This clarity not only minimizes ambiguity in information but also facilitates workflow visualization and awareness of action plans. However, effective visualization plays a crucial role in supporting lean principles, providing vital information such as task completion status, material availability, layout changes, and resource locations. This transparency enhances production planning and control, and ultimately reduces errors and inefficiencies (Sacks, Treckmann, & Rozenfeld, Visualization of Work Flow to Support Lean Construction, 2009).

Construction projects can employ various visualization methods, including mobile signs, notice boards, colored lines on floors, safety signage, project milestone markers, and production planning charts (Salem, Solomon, Genaidy, & Minkarah, 2006).

**Table 2-2** Lean Construction Principles and Techniques as Mentioned in Literature *

| Lean Principle | Lean Technique | Approach |
|---|---|---|
| Flow | Fail safe for quality | Prioritize upstream flow stabilization by minimizing project variations. |
| | Reduce batch size | |
| | Reduce cycle times | Minimize project lead times. |
| | reduce variability | Eliminate product variability to consistently achieve first-pass quality. |
| | Use reliable technology | e.g. 3D printing, BIM ...etc. |
| | Increase flexibility | Optimize transition efficiency between tasks. |
| Pull | Collaborative Planning | Prioritize demand-driven material management. |
| | Just-in-Time | |
| | Last planner | Pull scheduling approach |
| Continuous Improvement | Current State Mapping | As-Is Assessment: process flow value identification |
| | Future State Mapping | Idealized workflow modeling |
| | First-run studies | Applying the PDCA Cycle for Continuous Improvement |
| | Huddle meetings | Daily Briefing |
| Transparency | Five S's | Employ tools and techniques to make working methods transparent. |
| | Visual Management | Map the process flow. |

* (Salem, Solomon, Genaidy, & Minkarah, 2006); (Abdel-Razek, Abd Elshakour M, & Abdel-Hamid, 2007); (Sacks, Koskela, Dave, & Owen, 2010); (Eriksson, 2010)

## 2.6. Barriers to Implementation of Lean Construction Techniques

Many studies have been conducted internationally to determine the barriers to adapting techniques to reduce or eliminate construction waste. If not adequately managed, these barriers could have an influence on the LC application process and decrease project performance (Enshassi, Abo Elaish, & Arain, 2018). However, several barriers could prevent the use of LC techniques in construction industry (Cano, Delgado, Botero, & Rubiano, 2015). Furthermore, there are six categories of barriers to the adoption of LC in construction Industry: management, financial, educational, governmental, technical, and human attitude (Bashir, Suresh, Oloke, Proverbs, & Gameson, 2015).

### 2.6.1. .. Management Challenges

The commitment of top management to create and put into action a successful plan, provide the necessary resources, and manage changes resulting from the implementation is key to the success of the adoption of lean techniques (Shang & Sui Pheng, 2014). Moreover, adoption of lean tools by stakeholders in the construction industry may present several challenges, thus ongoing support from the top management is essential. (Bashir, Suresh, Oloke, Proverbs, & Gameson, 2015). However, various studies have observed several barriers, some of which are management related. Some of the managerial issues that were identified to be preventing the effective adoption of lean construction were poor project definition, a shortage of resources, delay in the delivery of materials, inadequate project definition, an ineffective plan, and a lack of client focus (Raghavan, Kalidindi, Mahalingam, Varghese, & Ayesha, 2014) (Bashir, Suresh, Oloke, Proverbs, & Gameson, 2015). Moreover, managers' opposition to change, unsuitable attitude, sluggish decision-making, Accepting waste as inevitable, lack of involvement and integration of all stakeholders, insufficient transparency, erroneous preplanning, inappropriate organizational structure, inadequate management, and poor procurement techniques, were recognized as LC implementing barriers by other studies (Sarhan & and Fox, 2012) (Aziz & Hafez, 2013) (Ogunbiyi O. , Implementation of the lean approach in sustainable construction: A conceptual framework., 2014) (Raghavan, Kalidindi, Mahalingam, Varghese, & Ayesha, 2014) (Bashir, Suresh, Oloke, Proverbs, & Gameson, 2015) (Cano, Delgado, Botero, & Rubiano, 2015)

### 2.6.2. .. Financial Challenges

Innovative ideas like lean construction must be implemented with sufficient funding to inspire employees, supply necessary tools and resources, and in certain circumstances, hire lean consultants or specialists to assist employers and employees in putting the strategy into practice. However, the most frequent obstacles to lean practices across several enterprises and nations are financial ones. (Wandahl, 2014) (Bashir, Suresh, Oloke, Proverbs, & Gameson, 2015) (Nowotarskia, Paslawskia, & Matyjaa, 2016). Thus, the need for financial resources for employee training programs and outside consultants is a major reason why lean techniques could fail (Ogunbiyi O. , Implementation of the lean approach in sustainable construction: A conceptual framework., 2014). Moreover, further studies have identified more of challenges to implementing lean tools on a financial level: low tender prices, inflation brought on by unstable construction markets, low professional salaries, absence of incentives or reward systems, the expense of implementation, and a lack of long-term prediction and investment. (Ayarkwa, Agyekum, Adinyira, & Osei-Asibey, 2015) (Marhani, Jaapar, Bari, & Zawawi, 2013) (Bashir, Suresh, Oloke, Proverbs, & Gameson, 2015) (Small, Al Hamouri, & Al Hamouri, 2017). However, Numerous businesses can be deterred from embracing lean if suitable measures aren't taken to address these issues.

### 2.6.3. .. Educational Challenges

The implementation of LC could be seriously threatened by educational challenges (Ogunbiyi, Oladapo, & Goulding, 2013). According to (Wandahl, 2014) Lack of knowledge, education, and experience are the three educational challenges to the use of lean techniques. Moreover, lack of awareness of lean, experience, culture in the workplace that encourages teamwork, and a lack of planning and prefabrication have been identified by further studies as the most common educational obstacles that could prevent the implementation of LC (Aziz & Hafez, 2013) (Ogunbiyi O. , 2014) (Raghavan, Kalidindi, Mahalingam, Varghese, & Ayesha, 2014) (Cano, Delgado, Botero, & Rubiano, 2015). Furthermore, the vast percentage of subcontractors, who frequently contribute to a project for a short period of time due to high turnover or the fact that contracted companies take on multiple projects without allocating staff to any particular project, this could impede the learning and exchange of knowledge (Skinnarland & Yndesdal, 2014) However, as people need to comprehend the reasons behind the need to change their current methods of doing things, upper management's high level of training and education of employees is crucial; else, they would resist changing. (Shang & Sui Pheng, 2014).

### 2.6.4. .. Governmental Challenges

Even though the construction industry contributes significantly to the economy of many nations, it still has several issues that are tied to governmental policy (Vieira

& Cachadinha, 2011). However, lean techniques adoption is hindered in some countries by issues such as inconsistent policy and volatile commodity prices. Nevertheless, government's bureaucracy and instability are seen as a major governmental related challenge (Ayarkwa, Agyekum, Adinyira, & Osei-Asibey, 2015) (Ogunbiyi, Oladapo, & Goulding, 2014) (Bashir, Suresh, Oloke, Proverbs, & Gameson, 2015).

### 2.6.5. .. Technical Challenges

Certain LC principles and techniques, like dependability, simplicity, adaptability, and benchmarking, are directly impacted by technical challenges (Koskela L. , 1992). Moreover, technical challenges, such as insufficient resources and delayed delivery of material , might impede implementation of lean techniques since they directly influence how they are utilized (Aziz & Hafez, 2013) (Ogunbiyi, Oladapo, & Goulding, 2014) (Raghavan, Kalidindi, Mahalingam, Varghese, & Ayesha, 2014) (Ayarkwa, Agyekum, Adinyira, & Osei-Asibey, 2015) (Bashir, Suresh, Oloke, Proverbs, & Gameson, 2015) (Cano, Delgado, Botero, & Rubiano, 2015). Furthermore, inadequate performance monitoring methodologies and the scattered character of the construction industry were identified as technical challenges to implementation of LC. (Small, Al Hamouri, & Al Hamouri, 2017).

### 2.6.6. .. Human Attitudinal Challenges

One of the key elements influencing the application of LC in the construction industry is human behavior (Bygballe & Sward, 2014). Likewise, (Bardalai & and Jayakumar, 2015) has mentioned that human attitude as one of the primary factors slowing down the adoption of LC, particularly during the practical implementation stage, is human attitude. Moreover, Insufficient leadership, socioeconomic issues including poverty, difficulty finding qualified individuals to use lean techniques, and misunderstandings about lean are the key human challenges. (Bardalai & and Jayakumar, 2015) (Bashir, Suresh, Oloke, Proverbs, & Gameson, 2015) (Cano, Delgado, Botero, & Rubiano, 2015). Furthermore, workers' aversion to change and their lack of collaboration were identified as human attitudinal challenges to implementation of LC.

## 2.7. Lean Implementation in Construction Industry

The lean approach has lately made its way into the construction sector, reforming conventional construction management methodology. Lean thinking has been applied and studied in several construction-related industries, including industrial and residential construction, finishing, concrete, and office-related activities. Hence, literature was traced, and research for adaption of lean principles in construction industry was conducted using following key words: “Lean Construction”, “Lean construction benefits”, “Lean Construction Implementation” “Lean management in construction industry”, “Lean construction practices” and “implementing lean construction”. Furthermore, searching process was timely limited to the period between (2011-2021) including only English written articles that had been published in peer-reviewed scientific journals. The lists that follow includes a few examples of how lean has been utilized in different construction sectors and main used lean tools:

### 2.7.1. Lean Construction Techniques Implementations

- **Residential Construction Projects**

Conducting in Nigeria, study aimed to evaluate the effectiveness of implementing lean tool i.e., Last Planner ® System (LPS) compared to the traditional methods. LPS tool was applied on a project of 300 housing units. Even though the management staff and workers followed instructions of not familiar with lean construction, LPS showed and proves a significant process improvement in terms of duration and performance. The study concluded that following the LPS approach would reduce waste and cost and improve profits. Moreover, the author recommended that all stakeholders in the industry should get involved in training and practice of lean construction techniques (Adamu & Howell, 2012).

- **Industrial Construction Projects**

This study conducted to evaluate the use of lean construction in China since it started to be implemented to construction industry in 2005. Data used in this study was collected by conducting a case study of an industrial building in a construction project in Suzhou, China from June to August 2019. Different lean tools were included in this study, for instance, LPS, Kanban system, JIT, prefabrication, Internet of Things (IoT), quality and safety management, and continuous improvement. Analyzing the collected data showed that implementation of lean practices during the project has improved total project performance. Moreover, a questionnaire survey conducted targeting construction global experts and stakeholders showed that utilizing lean tools would reduce waiting time and improve workflow along with project productivity and quality (Xing, Hao, Qian, Tam, & Sikora, 2021).

- **Infrastructure Projects**

a study conducted to evaluate utilizing lean management principles in complex projects to improve management efficiency. Adopting a quantitative approach, and a linear regression model, this study based on data collected using online and offline mediums to distribute questionnaire surveys among employees of five targeted construction firms working in highway construction projects, moreover the survey also distributed through emails and LinkedIn platform targeting participants who are involved or related to the construction sector. However, the result of analyzing collected data revealed that utilizing lean tools in highway construction projects is positively affecting its efficiency improvement. Furthermore, LPS, Just-In-Time (JIT), and Visual Management (VM) lean tools were found commonly used in highway construction projects. (Wu, Zhao, Ma, & Yang, 2019).

- **Construction submittal review process**

This study is a case study conducted to examine the effect of utilizing lean tool i.e., Value Stream Mapping (VSM) in the construction submittal review process; that may suffer of delays in submitting or responding phases. Results of this analyzing study revealed that application of lean to the process led to considerable total time reduction by eliminating non-value adding activities (Garrett & Lee, 2011).

- **Managing Construction On-site Storage Areas and Material Movement**

In this paper a case study conducted by presenting the idea of Lean Management Methodologies (LMM) to the construction of an office building in Poland aiming to show how the proposed methodology can influence the total cost of selected process. Wherefore, a deeper analysis was performed on introducing proposed methodology into the process of managing storage area focusing on economic aspect to show the influence of different styles of management on cost. However, Analyzing the successfully implemented proposed methodology solutions led to number of conclusions:

- The possibility of implementing LMM which was found to be efficient on the analyzed construction site.
- Confirmation of expected affection and results of applied improving methods for offering more storage space, quicker access for materials and reinforcement, while the savings on transportation, improvements of H&S and less in-site transportation were below expectation, furthermore, money savings were over expectation.
- Despite it is hard to estimate the influence and its cost reduction using systematic approach, LMM has affection on another actions and processes.
- Introducing LMM makes costs far lower, that provides savings for general contractors.

The analytical study led to the conclusion that LMM approach could be implemented in construction process, where changing the management of selected process showed a significant savings possibility in cost and time depending on how deep the implementation is and what tools are used (Nowotarskia, Paslawskia, & Matyjaa, 2016).

- **Enhancing Performance, Productivity, and Efficiency in Construction**

The effects of applying lean techniques enhancing performance, productivity, and efficiency in construction have been the subject of numerous research. (Abbasian-Hosseini, Nikakhtar, & Ghoddousi, 2014) conducted a study proposing computer simulation of construction operation with lean principles applied to evaluate effectiveness of implementing these principles. Bricklaying process simulation model built on data gathered construction sites was the case study of this paper. Simulation model results showed that implementing lean principles to the process reduced 41% of cycle time, increased productivity by 43%, and 27% increase in efficiency.

In another based on a comparative study which applied on simulated residential building project consists of two models. To evaluate and compare schedule performance of both models one of them implemented lean construction principles and the other did not apply them. However, analyzing results of followed method revealed that utilization of lean construction principles improved the performance of project from perspective of duration, by reducing total project duration and its expected variation.

Using discrete-event simulation (DES) approach, another case study was conducted to evaluate the impact of applying lean construction on performance. Along with collecting data of onsite reinforcement operation which observation, and interviewing construction managers evolved in the project, lean simulation model developed to validate and evaluate impact of lean construction on performance of case study process. Analysis and comparison of collected data from both onsite and simulation model revealed that Implementing lean principles in a construction process outperformed a traditional model by 41% productivity, 14% efficiency, and 17% faster cycle time. (Bajjou & Chafi, 2020).

A research study conducted in Nigeria aimed to assess the efficacy of employing select Lean Construction techniques in the construction of 80 housing units. The implemented techniques encompassed Last Planner System, Daily Huddle Meetings, and Enhanced Visualization. The findings revealed significant strides in time management, translating to substantial cost savings for the project. Notably, the project achieved completion in 62 days, a remarkable 31.11% improvement compared to the anticipated 90-day timeframe with traditional methods (Samaila & Adul Hamid, 2012).

- **Safety Performance in Construction**

A study conducted in Turkey to assess effectiveness of applying lean construction to increase safety performance. A questionnaire survey made to quantify the impact of lean implementation to collect needed data then the conceptual framework was tested and analyzed using Structural Equation Modelling. However, the study revealed that implementation of lean has a noticeable significant influence on safety performance of construction process (Demirkesen & Bayhan, 2020).

## 2.8. Lean Construction Simulation

Simulation modeling, as highlighted by (Van der Merwe, 2017) (Wang, Mohamed, Abourizk,, Asce, & Rawa, 2009), provides a robust avenue for assessing the anticipated influence of lean construction principles on construction processes before their physical implementation. Computer-enabled virtual simulation emerges as a highly effective and cost-efficient method for testing proposed lean construction processes. Leveraging the prowess of modern computing, virtual simulations enable the rapid examination of numerous process permutations, offering a robust validation tool prior to real-world implementation. This pre-emptive testing minimizes potential disruptions and optimizes the integration of lean principles on site (Mao & Zhang, 2008). For the simulation of lean principles, discrete-event simulation figures as a highly prevalent and effective technique (Sacks, Esquenazi, & Goldin, 2007). Further bolstering this connection, (Robinson, Radnor, Burgess, & Worthington, 2012) demonstrated the alignment between Discrete Event Simulation (DES) applications and the seven core waste principles identified in lean production. However, at its core, discrete-event simulation aims to mimic the operation of a system and elucidate its behavior over time through a sequence of events. Discrete-event simulation and management games both offer avenues for understanding and optimizing system behavior. While simulation excels at modeling complex operations through sequenced events, its practical implementation can be hindered by its intricate structure. Conversely, management games, focused on training purposes, provide a more readily accessible platform for exploring system dynamics (Alarcon & Ashley, 1999).

This study utilizes ARENA, a powerful discrete-event simulation software introduced by (Takus & Profozich, 1997), to effectively model and analyze construction processes. ARENA's intuitive graphical interface, built upon its robust SIMAN language platform and enhanced with versatile module templates, facilitates seamless modeling of uncertainties in task durations, timing, resource allocation, and material flow paths (Altiok & Melamed, 2007) . These capabilities make ARENA an ideal tool for construction process simulation within this research.

# 3 .. METHODOLOGY

This research employs a rigorous simulation modeling approach to investigate the potential benefits of integrating Lean techniques into traditional construction project management, with a specific focus on enhancing performance during the crucial monitoring and control phase. (Figure 3-1) depicts the sequential steps of the research methodology.

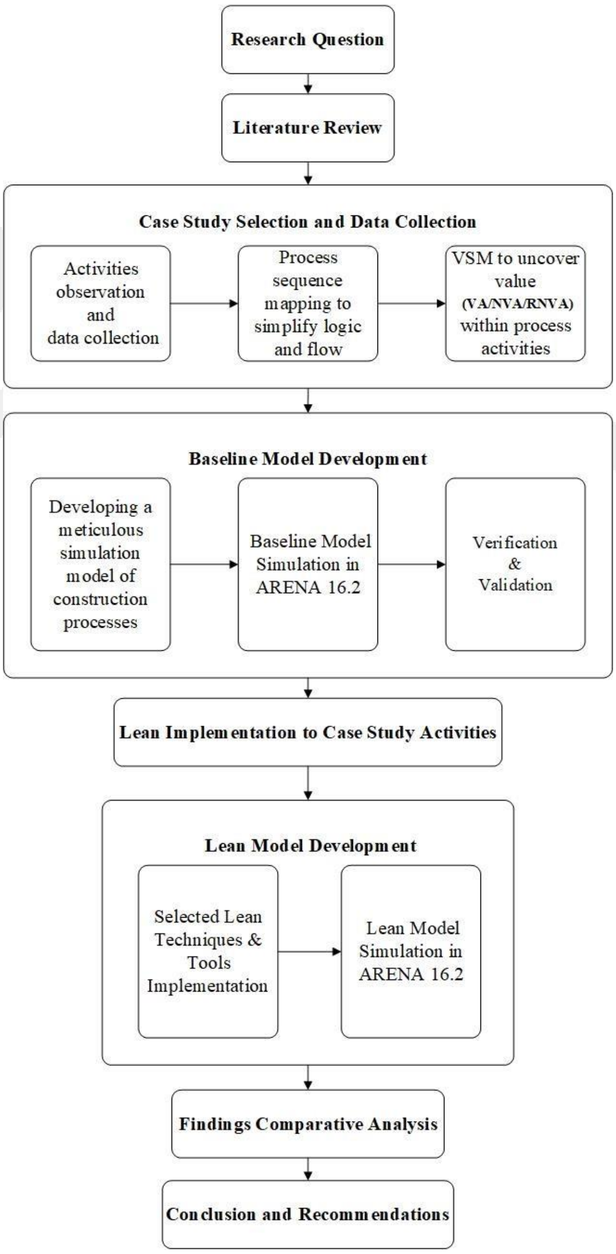



**Figure 3-1** Methodology Flowchart

### 3.1. Literature Review:

To establish a robust theoretical foundation, an extensive literature review was conducted. This review delved into:

- Exploring core principles, tools, and techniques of both Lean Management and Lean Construction frameworks.
- Examining quantitative and qualitative studies demonstrating Lean Construction's effectiveness in diverse project types.
- .. Reviewing existing studies utilizing simulation to compare performance under varied project management approaches.

This review identified knowledge gaps and informed the selection of specific Lean techniques for further investigation in the subsequent stages.

### 3.2. Case Study Selection and Data Collection:

To guarantee the applicability of our findings to a broader range of mid-sized projects, this research deliberately adopts a targeted single case study approach. We will meticulously investigate a project exhibiting key characteristics of its category, with its data subsequently informing the construction of the simulation models. This in-depth focus allows for a rigorous and thorough data collection process, involving the close observation of each one of the process activities. Through this observation, we aim to accurately ascertain actual durations and systematically identify and categorize all potential waste types. These detailed insights will then be used to generate a comprehensive process map depicting the activity sequence, alongside a complementary Value Stream Map (VSM). These visual representations will not only facilitate the identification of both bottlenecks and inefficiencies, but also highlight activities that directly contribute to the value added to the final project product.

### 3.3. Baseline Model Development:

Traditional estimates for construction activity durations heavily rely on historical data. However, when such data is scarce or lacking, alternative methods like expert opinions and onsite observations become crucial. This research employs a

Triangular Probability Density Function (TPDF) as described in Equation(3.1) to represent the variability of activity durations within the case study. The TPDF's strength lies in its ability to seamlessly incorporate inherent task variability by utilizing minimum ($a$), maximum ($b$), and most likely ($c$) duration estimates. These parameters can be derived from both readily available data, when available, and valuable expert insights, resulting in realistic project timelines even in data-scarce scenarios (Erol, Dikmen, & Birgonul, 2017).

$$f(x) = \begin{cases} \dfrac{(x-a)^2}{(b-a)(c-a)}, & a \leq x \leq c \\ 1 - \dfrac{(b-x)^2}{(b-a)(b-c)}, & c \leq x \leq b \end{cases}$$

**(3-1)**

Mean and standard deviation of TPDF can be calculated as:

$$\mu = \frac{1}{3}(a+b+c), \sigma = \sqrt{\frac{a^2+b^2+c^2-ab-ac-bc}{18}}$$

**(3-2)**

A detailed simulation model will be built to replicate the current state of the chosen construction process, encompassing actual workflow, resource allocation, and potential disruptions. The baseline model will be subjected to simulation using ARENA 16.2 software, replicating the actual construction process, and generating key performance indicators such as cycle time, lead time, which will serve as benchmarks for subsequent comparisons. Moreover, the inherent advantages of the triangular distribution, including its ease of parameter estimation and ability to effectively model uncertainty, have led to its widespread adoption in practical applications, as noted in the literature (Hajdu & Bokor, 2016) (Yang, 2005) (Wing, 1995).

To guarantee both intended functionality and internal consistency, the model will be subjected to a comprehensive verification process incorporating computational audits, code evaluation, and statistical uniformity assessments. This rigorous verification process further ensures the accuracy and reliability of the model. Ensuring the reliability of findings, the model results will be validated against real-world observations, enhancing research credibility and practical applicability.

### 3.4. Lean Implementation to Case Study Activities:

Drawing upon the waste types identified in the baseline model, specific Lean construction techniques will be strategically deployed. This selection, which may encompass continuous flow, pull planning, standardized work, Kanban boards, and just-in-time delivery, among others, will be subsequently integrated into a dedicated "Lean Scenario" This scenario will model the impact of the chosen techniques on key aspects such as process flow, resource allocation, and waste reduction/elimination. This allows for a comparative analysis with the non-lean scenario, highlighting the potential performance improvements enabled by Lean principles.

### 3.5. Lean Construction Model Development:

A new simulation model will be constructed, integrating enhancements derived from Process and Operation Optimization Lean principles. This model will analyze the influence of these principles on process flow and waste reduction/elimination. To ensure a valid comparison, a corresponding baseline model will be meticulously constructed mirroring the scope, initial conditions, and external factors of the Lean model. This rigorous control allows for the isolated evaluation of the Lean techniques' impact, providing clear insights into their effectiveness.

### 3.6. Findings Comparative Analysis:

Following their development, the key outputs of both the Lean and baseline models will be subjected to a rigorous comparative analysis and evaluation. This comprehensive assessment aims to address the principal research question, centered on the impact of integrating Lean tools and techniques within the construction activities of the chosen case study on overall project duration and its efficiency. Informed by both the researcher's personal observations and established simulations outputs, the resulting analysis will be thoroughly illustrated. Equation (3.2) provides the mathematical formula for calculating project efficiency.

$$Construction\ Process\ Efficiency\ (PCPE) = \frac{Total\ Value\ Adding\ Activities\ Duration}{Total\ Construction\ Process\ Time} \times 100$$

**(3-3)**

### 3.7. Conclusion and Recommendations:

The study's limitations and the generalizability of its findings to other construction contexts and project types will be thoroughly discussed, enabling context-specific interpretations and future research directions.

# 4 .. IMPLEMENTATION AND RESULTS

## 4.1. Case Study Selection and Data Collection

This case study examines the construction of a new crusher for a cement factory in Saudi Arabia. The project comprises five primary civil works components: retaining walls, the main crusher building, conveyor columns, transfer tower foundations and columns, and service buildings. While (Table 4-1) provides further project details, this research primarily investigates the construction process of the retaining wall and any associated activities.

**Table 4-1** Case Study Project Data.

| Item | Description |
| --- | --- |
| Project Location | Cement Plant in Saudi Arabia |
| Project Type | Construction |
| Project Value | 10M SAR |
| Contract Type | Unit Price |
| Scope of Contract | Concrete Works Execution |
| Project Quantities | Excavation: 17,486 $m^3$, Concrete: 2,614.79 $m^3$, Rebars: 316 t |

(Figure 4-1) provides a visual representation of the entire project area, pinpointing the specific locations where the research case study was conducted. These locations include the retaining wall, storage area, and workshop.


**Figure 4-1** Case Study Project Layout

### 4.1.1. .. Activities Process Map

According to (Al-Sudairi, 2007) the first step towards the creation of a simulation model is to describe process activities and their sequences, as well as labor force and workflow followed in construction of retaining walls in the above-mentioned construction project. Process mapping can effectively visualize the interconnectedness of resources, activities, and information flow. Within the chosen project segment, the following activities were identified and subsequently elaborated upon and categorized as depicted in process map of (Figure 4-4):

1. Formwork Installation for Plain Concrete.
2. Concrete Casting for Plain Concrete.
3. Rebars Installation for Foundation.
4. Formwork Installation for Foundation.
5. Concrete Casting for Foundation.
6. Backfilling and Compaction Around Foundation.
7. Rebars Installation for Retaining Wall.
8. Formwork Installation for Retaining.
9. Concrete Casting for Retaining Wall.

(Figure 4-2) and (Figure 4-3) present visual observations from the case study construction site, capturing the sequential activities involved in retaining wall construction. These activities as previously stated are placement of plain concrete, followed by the foundation, backfilling, and finally, the construction of the retaining wall itself.

**Figure 4-2** On-Site Observations for Plain Concrete, Foundation, & Backfilling.

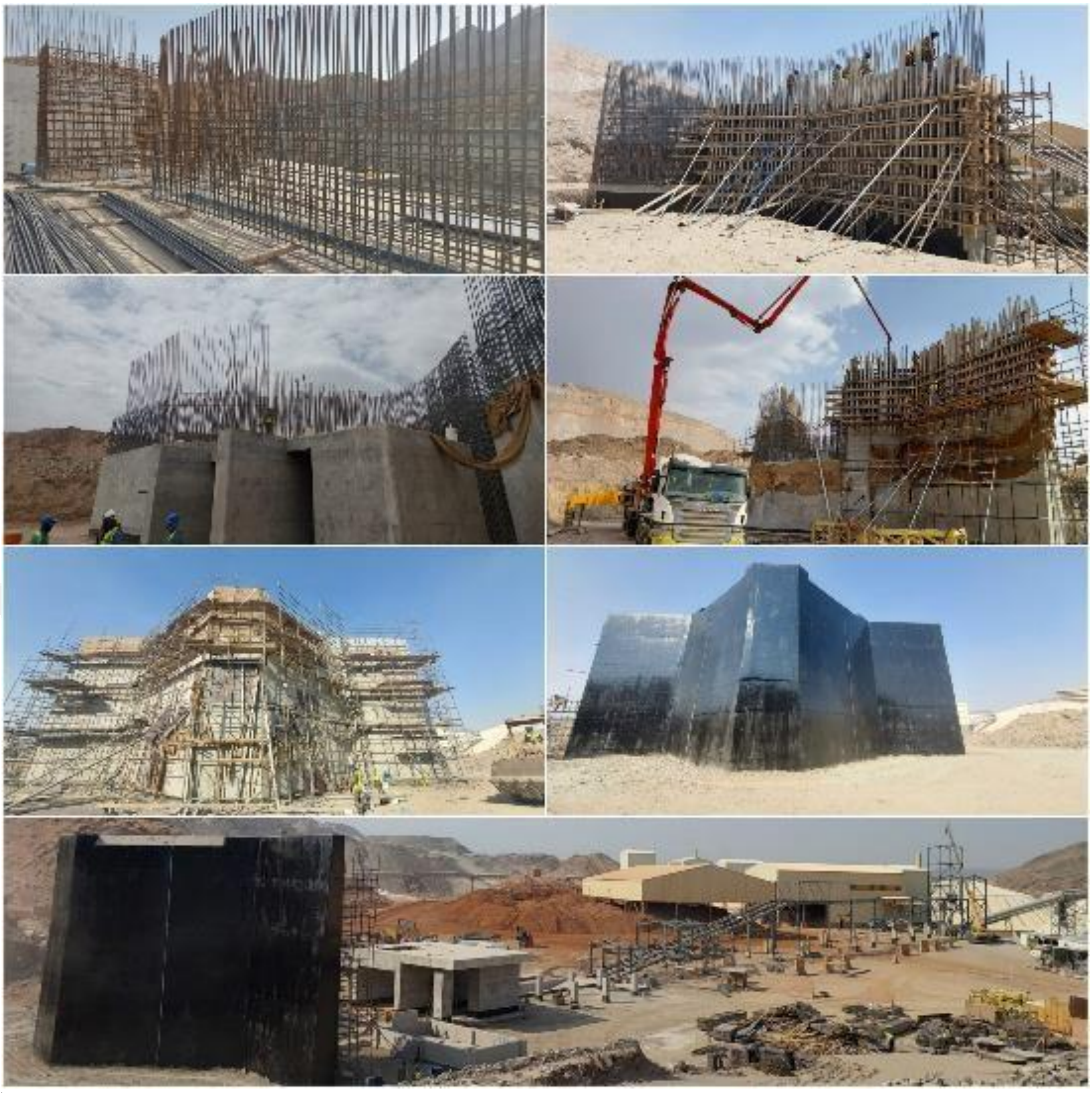


**Figure 4-3** On-Site Observations for Retaining Wall Construction.

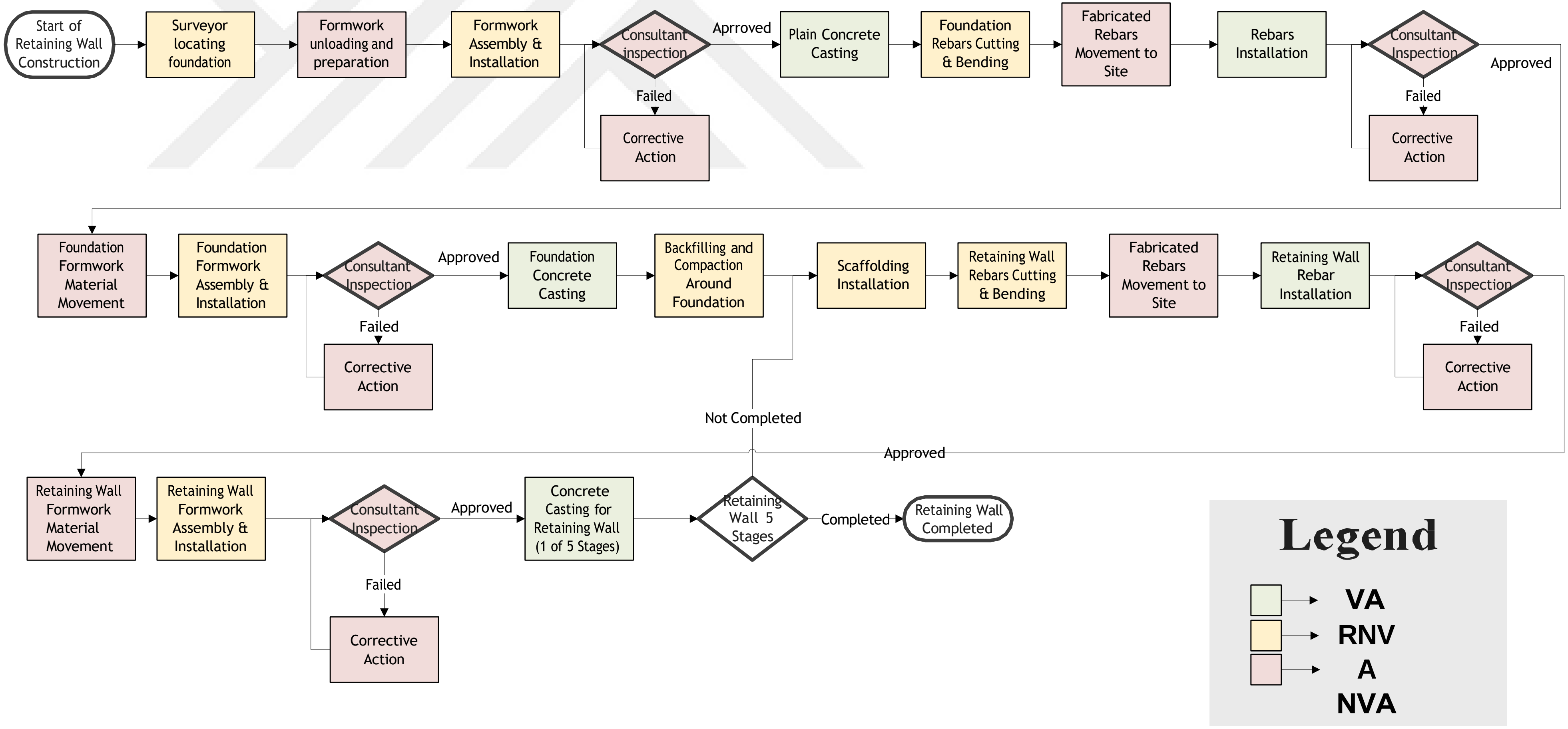



**Figure 4-4** Process Map of Observed Retaining Wall Construction.

In construction industry any non-value adding activity, disruption or delay is considered waste, though, before this waste can be eliminated there has to be correct identification on it; this research utilizes value stream mapping to provide a clear view of the existing processes with the aim of understanding what adds value in them in terms of their physical aspects and which are non-physical wastes that can be worked upon for improvement. The identification process itself is structured into two major stages which are Value and Waste Identification then Waste Analysis.

#### 4.1.2. .. Value Identification.

*Value and Waste Identification*

Building on previous lean methodology reviewed on Value Stream Mapping (VSM) for Lean Construction, this study developed a current state map detailing durations for value-adding (VA), non-value adding (NVA), and required non-value adding (RNVA) activities within a case study example from building construction industry. The main objective of utilizing VSM was two-fold: firstly, to understand non-physical lean waste flows throughout project lifecycle and secondly, to identify root causes of their emergence. Finally, this approach aimed to reduce waste, maximize resources employment process, and enhance time and material efficiency.

Activities were monitored closely, and their durations recorded including waiting times for retaining wall construction process (including plain concrete footing and reinforced concrete raft) during the targeted construction phase whose current state map is shown in (Figure 4-5). This data focuses solely on this specific phase of the project.

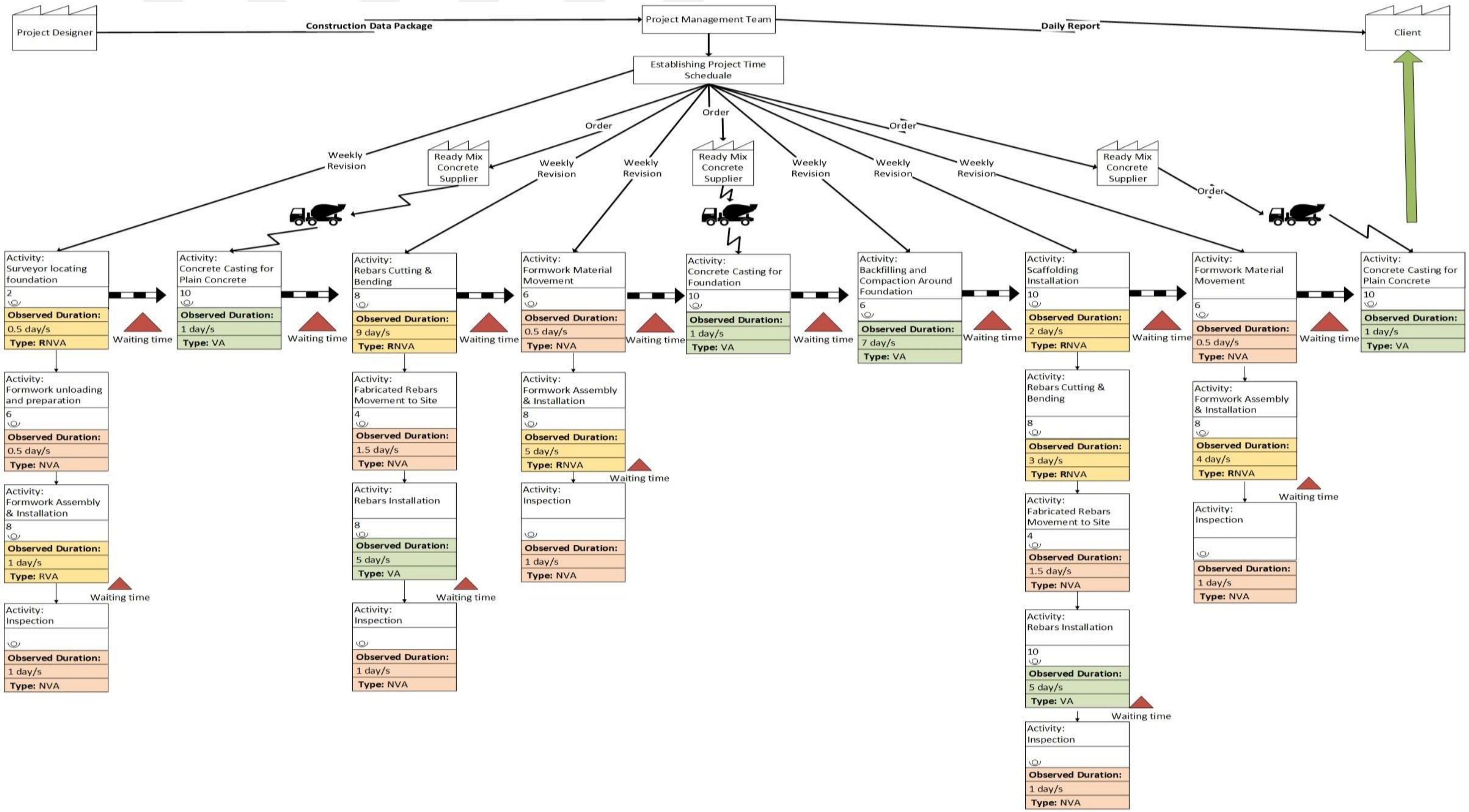



**Figure 4-5** Current State Map for Case Study.

(Table 4-2) shows a summary of the observed durations, resources, and value-adding classifications of activities involved in the retaining wall construction process.

**Table 4-2** Process Activities Durations, Resources, and Type.

| Act. No. | Activity | Sub-Activity | Duration (Days: 8hrs) | Manpower | Activity Classification |
|---|---|---|---|---|---|
| 1 | Formwork Installation for Plain Concrete | Surveyor locating foundation | 0.50 | 2 | RNVA |
| | | Formwork unloading and preparation | 0.50 | 6 | NVA |
| | | Plain Concrete Formwork Assembly & Installation | 1.00 | 8 | RNVA |
| | | Inspection | 1.00 | N/A | NVA |
| 2 | Concrete Casting for Plain Concrete | - | 1.00 | 10 | VA |
| 3 | Rebars Installation for Foundation | Foundation Rebars Cutting & Bending | 9.00 | 8 | RNVA |
| | | Fabricated Rebars Movement to Site | 1.50 | 6 | NVA |
| | | Rebars Installation | 5.00 | 10 | VA |
| | | Inspection | 1.00 | N/A | NVA |
| 4 | Formwork Installation for Foundation | Foundation Formwork Material Movement | 1.00 | 6 | NVA |
| | | Foundation Formwork Assembly & Installation | 5.00 | 8 | RNVA |
| | | Inspection | 1.00 | N/A | NVA |
| 5 | Concrete Casting for Foundation | - | 1.00 | 10 | VA |
| 6 | Backfilling and Compaction Around Foundation | - | 7.00 | 6 | RNVA |
| 7 | Rebars Installation for Retaining Wall (5 Stages) | Scaffolding Installation | 10.00 | 6* | RNVA |
| | | Retaining Wall Rebars Cutting & Bending | 15.00 | 8* | RNVA |
| | | Fabricated Rebars Movement to Site | 7.50 | 6* | NVA |
| | | Retaining Wall Rebar Installation | 25.00 | 10* | VA |

| Act. No. | Activity | Sub-Activity | Duration (Days: 8hrs) | Manpower | Activity Classification |
|---|---|---|---|---|---|
| | | Inspection | 5.00 | N/A | NVA |
| 8 | Formwork Installation for Retaining Wall (5 Stages) | Retaining Wall Formwork Material Movement | 5.00 | 6* | NVA |
| | | Retaining Wall Formwork Assembly & Installation | 20.00 | 8* | RNVA |
| | | Inspection | 5.00 | N/A | NVA |
| 9 | Concrete Casting for Retaining Wall (5 Stages) | - | 5.00 | 10* | VA |
| **Total Observed Duration (days)** | | | **133** | | |

* Amount of Manpower for one Stage

### 4.1.3. Waste Analysis.

*Value Stream Map Analysis.*

An initial mapping identified 23 sub-activities which encompassed components of VA, NVA, RNVA and waiting time subsequent classification of these activities produced the following notable findings:

- A total of five VA activities that took 37 days, or 27.82% out of total 133 day's observation period (Figure 4-6).
- 8 RNVA activities which are considered as non-value adding consumed 67.50 days accounting for 50.75% against 133-day's total observed duration (Figure 4-6).
- A significant portion of the process activities identified (10 in total) were classified as non-value-adding (NVA). These NVA activities collectively consumed 28.50 days, representing 21.43% of the total observed process duration of 133 days (Figure 4-6).

The construction of retaining wall exhibits a concerning imbalance, with non-value-adding and required non-value-adding activities (NVA & RNVA = 72.18%) nearly outweighing value-adding activities (VA = 27.82%). Implementing lean construction techniques and methods could potentially identify and eliminate non-contributory activities, improving overall efficiency and eventually reducing project costs.

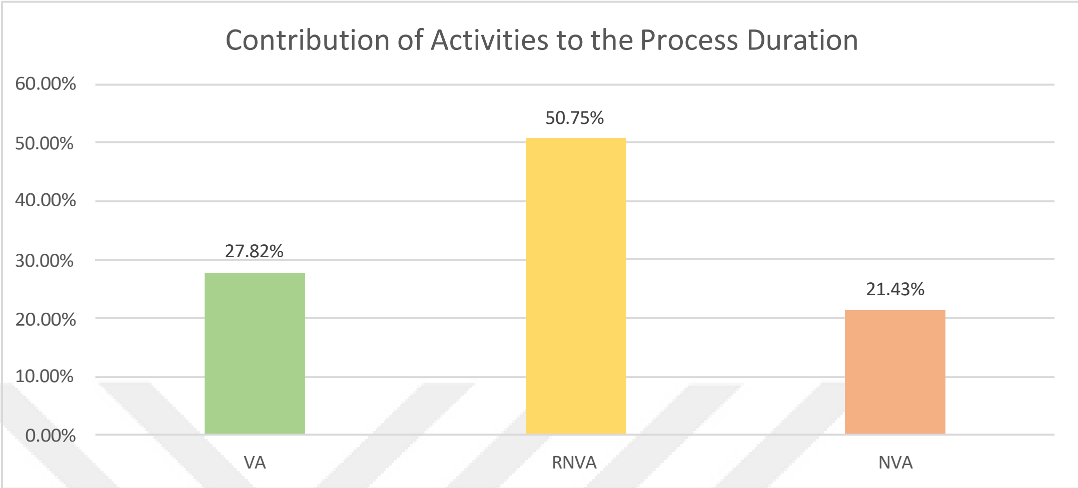



**Figure 4-6** Contribution of Activities to the Total Process Duration.

*On Site Observed Wastes*

Despite its merits, challenges and limitations within the PM approach necessitate investigation and innovative solutions. The present study addresses this need by analyzing the application of PM in medium scale construction project, specifically focusing on uncovering weaknesses and hindrances that compromise project productivity by closely observing the performance of various tasks and daily routines within the retaining wall construction process. As outlined earlier, these hindrances are conceptualized as "wastes" within the simulation model employed in this research. (Table 4-3) categorizes the observed wastes based on the principles of Lean Construction waste identification.

### *First Observed Waste (W1):*

Analysis of the first stage of retaining wall construction revealed a concerning 5% rate of fabricated rebars requiring repair or scrapping due to defects. This suggests systemic quality control issues, particularly at the cutting workstation, where the most frequent defect observed was incorrectly cut rebars (wrong dimension or size). These defective rebars not only necessitated rework but also resulted in additional costs and time during subsequent processing, such as bending and transporting.

### *Second Observed Waste (W2)*

Inefficient project layout, characterized by distant storage of equipment and tools, resulted in unnecessary personnel movement and extended activity durations, ultimately impacting project efficiency.

### *Third Observed Waste (W3)*

Ineffective planning and miscalculated material requirements resulted in a critical shortage of shuttering materials, which in turn induced multiple formwork delays of 2-3 days each. These disruptions adversely affected project efficiency and timeline.

### *Fourth Observed Waste (W4)*

Assigning distinct, non-versatile teams to specific tasks hampers adaptability and resource reallocation. This inflexibility impedes efficient workflow when tasks or priorities shift, leading to underutilized workers and potential delays.

### *Fifth Observed Waste (W5)*

Premature rebar fabrication resulted in an inventory surplus, which in turn induced overproduction and its attendant negative consequences. These include potential material deterioration necessitating rework, as well as the cost burden of scrapping damaged rebars.

**Table 4-3** Observed Wastes According to Lean Construction Waste Types.

| No. | Observed Waste | Lean Construction Identification |
|---|---|---|
| W1 | Inaccuracies in rebar fabrication manifested as deviations from intended lengths, cross-sectional dimensions, and bending configurations. | Defects / Overprocessing |
| W2 | The extended travel time required to retrieve necessary equipment and tools from remote storage sites. | Unnecessary Movement |
| W3 | Inadequate availability of formwork components. | Waiting |
| W4 | Specialized Crews and Limited Worker Flexibility | Underutilized |

| No. | Observed Waste | Lean Construction Identification |
|---|---|---|
| | | People |
| W5 | Fabricating rebars earlier than needed. | Excess Inventory / Overproduction |

## 4.2. Simulation Baseline Model Development.

### 4.2.1. .. Baseline Model Simulation in ARENA 16.2.

Building upon the documented advantages of simulation identified in the existing literature review, this research implements simulation modeling to assess the potential impact of integrating lean construction principles into the retaining wall construction process. To establish a benchmark for analysis, a comprehensive baseline model was constructed, replicating the collected data of the subject process. Sub-activity durations were tailored to a Triangular Probability Density Function, with parameters informed by on-site observations and expert judgments. Utilizing ARENA 16.2 software, this baseline model serves as a fundamental reference point throughout the analysis. Subsequent iterations incorporating lean principles, termed the "lean construction" scenario, will be compared against this robust baseline to evaluate the effectiveness of the proposed improvements. (Figure 4-7) illustrates the baseline model's representation in Arena software.

Retaining wall construction activities are characterized by their probability density functions and distribution parameters, as shown in (Table 4-4).

**Table 4-4** Triangular Distribution Parameters of Baseline Model Activities.

| Act. No. | Activity | Sub-Activity | Activity Quantity | Triangular Parameters (days) |
|---|---|---|---|---|
| 1 | Formwork Installation for Plain Concrete | Surveyor locating foundation | - | (0.25, 0.5, 1) |
| | | Formwork unloading and preparation | - | (0.25, 0.5, 0.75) |
| | | Plain Concrete Formwork Assembly & Installation | $20m^2$ | (0.5, 1, 1.5) |
| | | Inspection | - | (0.5, 1, 1.5) |
| 2 | Concrete Casting for Plain Concrete | - | $56\ m^3$ | (0.25, 1, 1.5) |
| 3 | Rebars | Foundation Rebars Cutting & | 88.9 t | (6, 9, 12) |

| Act. No. | Activity | Sub-Activity | Activity Quantity | Triangular Parameters (days) |
|---|---|---|---|---|
| | Installation for Foundation | Bending | | |
| 4 | | Fabricated Rebars Movement to Site | | (0.75, 1.5, 2) |
| 5 | | Rebars Installation | | (3, 5, 7) |
| 6 | | Inspection | - | (0.5, 1, 2) |
| 7 | Formwork Installation for Foundation | Foundation Formwork Material Movement | 200 $m^2$ | (0.5, 1, 1.5) |
| 8 | | Foundation Formwork Assembly & Installation | | (3, 5, 6) |
| 9 | | Inspection | - | (0.5, 1, 1.5) |
| 10 | Concrete Casting for Foundation | - | 875 $m^3$ | (0.75, 1, 2) |
| 11 | Backfilling and Compaction Around Foundation | - | 400 $m^3$ | (4, 7, 8) |
| 12 | Rebars Installation for Retaining Wall* | Scaffolding Installation and Safety Inspection | - | (1.5, 2, 3) |
| 13 | | Retaining Wall Rebars Cutting & Bending | 17.9 t/stage | (2, 3, 4) |
| 14 | | Fabricated Rebars Movement to Site | | (0.75, 1.5, 2) |
| 15 | | Retaining Wall Rebar Installation | | (2.5, 5, 6) |
| 16 | | Inspection | - | (0.5, 1, 1.5) |
| 17 | Formwork Installation for Retaining Wall* | Retaining Wall Formwork Material Movement | 586.2 $m^2$/stage | (0.5, 1, 1.5) |
| 18 | | Retaining Wall Formwork Assembly & Installation | | (3, 4, 5) |
| 19 | | Inspection | | (0.5, 1, 1.5) |
| 20 | Concrete Casting for Retaining Wall* | - | 142 $m^3$ / stage | (0.75, 1, 1.5) |

***** Duration indicators for 1 stage of retaining wall.

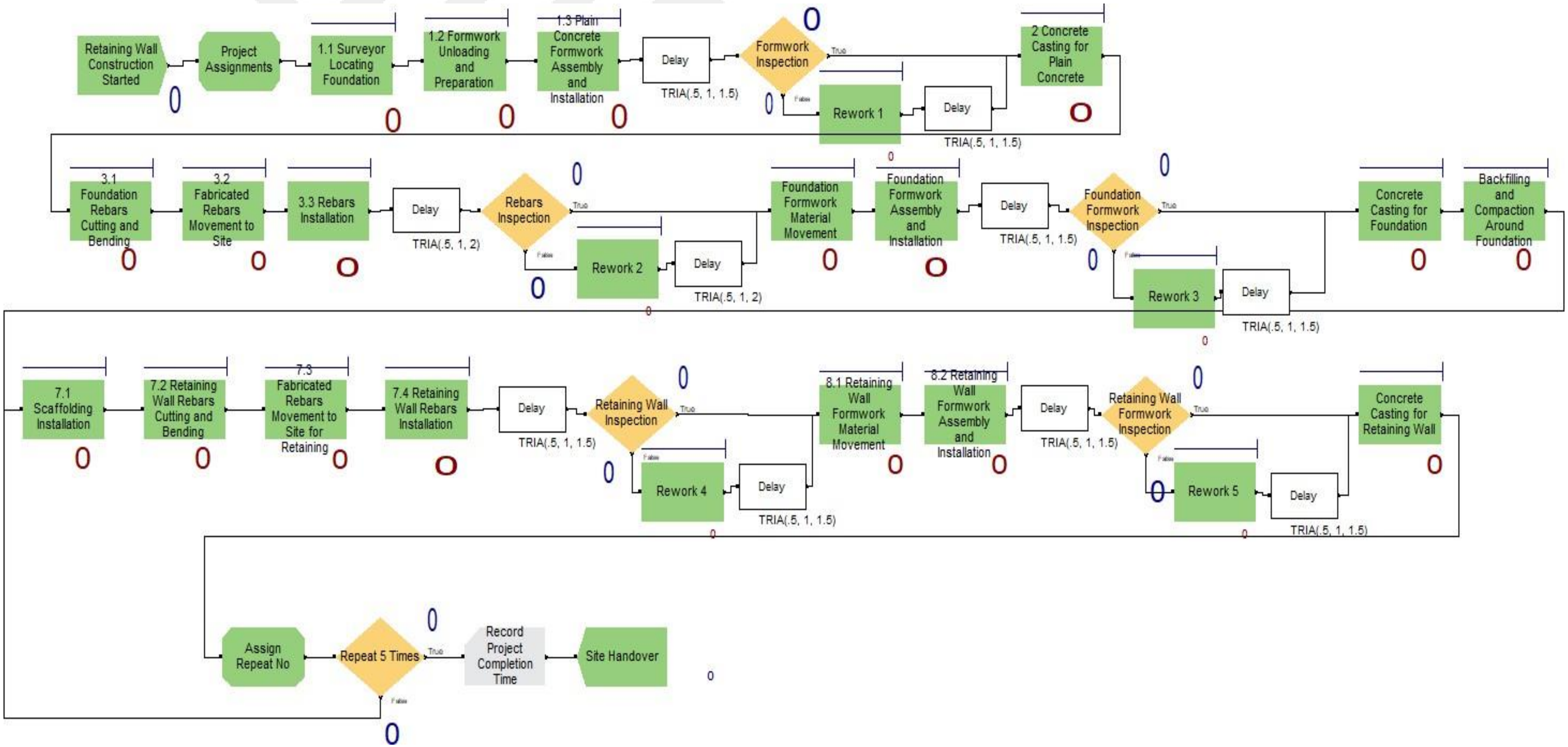



**Figure 4-7** Baseline Model with Reworks in Arena.

### 4.2.2. .. Baseline Model Validation

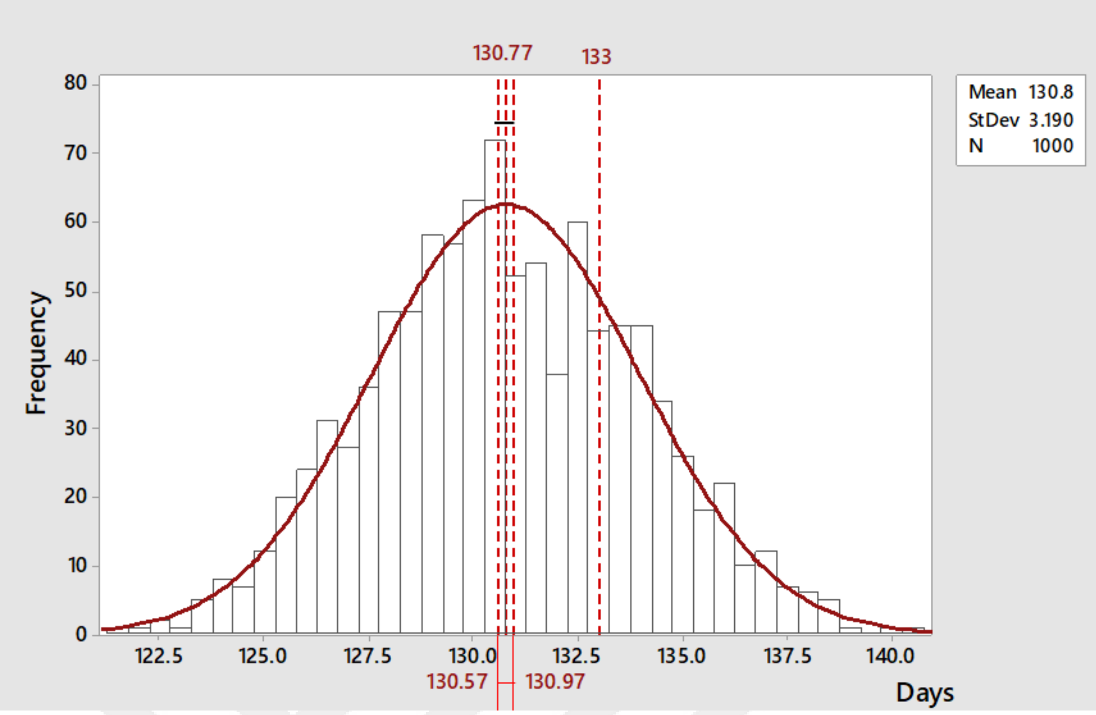
Model validation ensures the developed simulation reflects the behavior of the existing system (Farrar, AbouRizk, & Mao, 2004) (Bajjou & Chafi, 2020). This is achieved by comparing simulated outputs against real-world data collected from the studied process (Banks, Carson, Nelson, & Nicol, 2005). Cycle time, defined as the total time to move a unit through a process (Maunzagona, 2017), serves as a key metric for assessing real-world resemblance. Notably, time carries greater weight than quality or cost as it directly influences both (Krupka, Joseph, & Compton, 1992).

Due to the scarcity of the measurement data, the Total Observed Duration of 133 days was assumed as the sole benchmark to prove the validity of the base simulation model. Therefore, we are after testing the hypothesis:

$$H_0: \mu_{SIM} = 133 \text{ days}$$

$$H_1: \mu_{SIM} \neq 133 \text{ days}$$

where $\mu_{SIM}$ represents the mean project completion time parameter of the base simulation model. (Figure 4-8) shows the resulting histogram and summary statistics when the base model replicated 1000 times. Relative positions of the hypothesized mean, simulation mean, lower and upper 95% confidence interval (CI) limits can be seen. Although the 95% CI does not include hypothesized 133 days, relatively speaking, the difference (133–130.77)/133 = 1.7%) can be regarded practically insignificant. As a result, although we cannot claim full statistical validation, it has been concluded that the model can produce consistent results, and the same parameters can be used in the continuation of the study.




| Summary Stats. | Average | Std.Dev. | 95% CI for Mean | Min | Max | # of Reps |
|---|---|---|---|---|---|---|
| Project Total Time with Reworks | 130.77 | 3.19 | $130.57 \leq \mu_{SIM} \leq 130.97$ | 121.71 | 140.48 | 1000 |

**Figure 4-8** Histogram and summary statistics of Base model with 1000 replications.

### 4.3. Lean Techniques Implementation to Case Study

Building upon insights gained from waste identification, this research adopts a Lean framework to examine the effectiveness of implementing various Lean tools and techniques within the retaining wall construction case study. Through their application, the research aims to quantify their influence on project performance and construct a forward-looking blueprint for process optimization. To guarantee flow throughout the process, several specific lean techniques were employed, detailed as follows:

- Collaboration.
- Coordination.
- Five S.
- ....Get Quality Right at First Time.
- ....Just-In-Time.
- ....Last Planner System.

- ....Use Reliable Technology.
- ....Visualization.

(Table 4-5) delves into the application of the previously discussed Lean techniques across the multifaceted activities of the retaining wall construction process. This analysis pinpoints the strategies employed to minimize or eliminate various waste forms within each activity, fostering overall process optimization. Subsequently, sub-activity durations were adjusted to reflect the impact of the implemented Lean framework on the case study, as informed by expert judgments presented in (Table 4-8)

**Table 4-5** Implementing Lean Techniques/Tools to Case Study Activities.

<table>
<tr><th>Act. No.</th><th>Activity</th><th>Sub-Activity</th><th>Cause of Waste</th><th>Lean Construction Implementation</th><th>Lean Scope</th><th>Lean Technique / Tool</th><th>Activity Type</th></tr>
<tr><td rowspan="4">1</td><td rowspan="4">Formwork Installation for Plain Concrete</td><td>Surveyor locating foundation</td><td>Lack of information & Coordination</td><td>Technical office-site engineer coordination.</td><td>Pull</td><td>Coordination / Collaboration</td><td>RNVA</td></tr>
<tr><td>Material unloading and preparation</td><td>Late material delivery</td><td>Collaborative efforts with the supplier ensured timely material delivery</td><td>Pull</td><td>Just-in-time / Coordination</td><td>NVA</td></tr>
<tr><td>Plain Concrete Formwork Assembly & Installation</td><td>Low productivity</td><td>daily performance monitoring</td><td>Flow</td><td>Last Planner System</td><td>RNVA</td></tr>
<tr><td>Inspection</td><td>Poor quality</td><td>Execution monitoring and quality evaluating</td><td>Flow</td><td>Get Quality First Time</td><td>NVA</td></tr>
<tr><td>2</td><td>Concrete Casting for Plain Concrete</td><td>-</td><td>Transport issues (long distance)</td><td>Collaborative efforts with the supplier ensured timely material delivery</td><td>Pull</td><td>Just-in-time / Coordination</td><td>VA</td></tr>
<tr><td rowspan="4">3</td><td rowspan="4">Rebars Installation for Foundation</td><td>Foundation Rebars Cutting & Bending</td><td>Inaccuracies in rebar fabrication / over-production</td><td>Technical office-site engineer coordination / Intensive quality control / Fabricate only when needed</td><td>Pull / Flow</td><td>Coordination / Get quality first time / Just-in-time</td><td>RNVA</td></tr>
<tr><td>Fabricated Rebars Movement to Site</td><td>Unnecessary movement</td><td>Deliver rebars only when needed at the site / Kanban cards to signal rebar needs from the site to the workshop</td><td>Pull / Flow</td><td>Just-in-time / Visualization</td><td>NVA</td></tr>
<tr><td>Rebars Installation</td><td>low productivity of labors</td><td>On-site sorting for smoother progress / Track progress visually on the Status Board for laborers and supervisors / creating a detailed reverse schedule / Supervisors implement weekly workload planning and daily performance monitoring of laborers / Implement the use of BIM</td><td>Pull / Flow</td><td>5S / Coordination / Last Planner System / Visualization / Use reliable technology</td><td>VA</td></tr>
<tr><td>Inspection</td><td>Poor quality</td><td>Execution monitoring and quality evaluating</td><td>Flow</td><td>Get Quality First Time</td><td>NVA</td></tr>
</table>

| Act. No. | Activity | Sub-Activity | Cause of Waste | Lean Construction Implementation | Lean Scope | Lean Technique / Tool | Activity Type |
|---|---|---|---|---|---|---|---|
| 4 | Formwork Installation for Foundation | Foundation Formwork Material Movement | Unnecessary movement | On-site sorting for smoother progress / track the flow of materials and identify bottlenecks | Flow | 5S / Visualization | NVA |
| | | Foundation Formwork Assembly & Installation | low productivity of labors | On-site sorting for smoother progress / Track progress visually on the Status Board for laborers and supervisors / creating a detailed reverse schedule / Supervisors implement weekly workload planning and daily performance monitoring of laborers / Implement the use of BIM | Pull / Flow | 5S / Coordination / Last Planner System / Visualization / Use reliable technology | RNVA |
| | | Inspection | Poor quality | Execution monitoring and quality evaluating | Flow | Get Quality First Time | NVA |
| 5 | Concrete Casting for Foundation | - | Transport issues (long distance) | Collaborative efforts with the supplier ensured timely material delivery | Pull | Just-in-time / Coordination | VA |
| 6 | Backfilling and Compaction Around Foundation | - | Late material and rental equipment delivery | Collaborative efforts with the supplier ensured timely material and equipment delivery | Pull | Just-in-time / Coordination | RNVA |
| 7 | Rebars Installation for Retaining Wall (5 Stages) | Scaffolding Installation and Safety inspection | Unnecessary movement / Poor installation quality | On-site sorting for smoother progress / track the flow of materials and identify bottlenecks / Execution monitoring and quality evaluating | Flow | 5S / Visualization / Get Quality First Time | RNVA |
| | | Retaining Wall Rebars Cutting & Bending | Inaccuracies in rebar fabrication / over-production | Technical office-site engineer coordination / Intensive quality control / Fabricate only when needed | Pull / Flow | Coordination / Get quality first time / Just-in-time | RNVA |
| | | Fabricated Rebars Movement to Site | Unnecessary movement | Deliver rebars only when needed at the site / Kanban cards to signal rebar needs from | Pull / Flow | Just-in-time / Visualization | NVA |

| Act. No. | Activity | Sub-Activity | Cause of Waste | Lean Construction Implementation | Lean Scope | Lean Technique / Tool | Activity Type |
|---|---|---|---|---|---|---|---|
| | | | | the site to the workshop | | | |
| | | Retaining Wall Rebar Installation | low productivity of labors | On-site sorting for smoother progress / Track progress visually on the Status Board for laborers and supervisors / creating a detailed reverse schedule / Supervisors implement weekly workload planning and daily performance monitoring of laborers / Implement the use of BIM | Pull / Flow | 5S / Coordination / Last Planner System / Visualization / Use reliable technology | VA |
| | | Inspection | Poor quality | Execution monitoring and quality evaluating | Flow | Get Quality First Time | NVA |
| 8 | Formwork Installation for Retaining Wall (5 Stages) | Retaining Wall Formwork Material Movement | Unnecessary movement | On-site sorting for smoother progress / track the flow of materials and identify bottlenecks | Flow | 5S / Visualization | NVA |
| | | Retaining Wall Formwork Assembly & Installation | low productivity of labors | On-site sorting for smoother progress / Track progress visually on the Status Board for laborers and supervisors / creating a detailed reverse schedule / Supervisors implement weekly workload planning and daily performance monitoring of laborers / Implement the use of BIM | Pull / Flow | 5S / Coordination / Last Planner System / Visualization / Use reliable technology | RNVA |
| | | Inspection | Poor quality | Execution monitoring and quality evaluating | Flow | Get Quality First Time | NVA |
| 9 | Concrete Casting for Retaining Wall (5 Stages) | - | Transport issues (long distance) | Collaborative efforts with the supplier ensured timely material delivery | Pull | Just-in-time / Coordination | VA |

## 4.4. Simulation Lean Model Development

### 4.4.1. .. Lean Implementation to Baseline Model

To bridge the gap between theoretical Lean principles and their practical application in construction, this research utilizes a simulated environment. Through the targeted implementation of specific Lean principles/tools within the baseline model, the study quantifies their potential impact and generates practical guidelines for integrating Lean thinking into traditional management approaches. This simulation model fosters the wider adoption of Lean within the construction industry by offering a tangible example of its benefits. (Table 4-6) details the implementation of key Lean principles within Baseline model to establish Lean simulation model.

Minimizing project total duration along with maximizing efficiency in the retaining wall construction process were the aim of this model, achieved through the two-pronged approach of enhancing process flow and resource utilization, coupled with the prioritization of the "Get Quality First Time" principle. Activities were strategically redesigned to facilitate potential simultaneous execution whenever dependencies allowed. This, in turn, led to dependency decoupling, where the feasibility of initiating subsequent activities before complete predecessor finalization was investigated. Enabling overlapping activity streams resulted in substantial time savings. This flexible activity sequencing further enhanced the potential for project schedule optimization. Subsequently, with a relentless focus on eradicating rework as a central objective, the process map for the lean model was revised in accordance with the "Get Quality First Time" principle, allowing its potential impact on construction processes to be assessed.

### 4.4.2. .. Lean Model Simulation in ARENA 16.2.

Based on a Precise analysis of potential parallel task execution and non-value-adding (NVA) reduction or elimination opportunities, (Figure 4-9) presents an enhanced process map for retaining wall construction. This visual representation depicts the activity sequence, emphasizing NVA removal, potential overlaps, and opportunities for concurrent workstreams, with the aim of enhancing overall project efficiency and reducing lead time. For instance, the Baseline model reflected typical construction practices, with activities completed sequentially. In contrast to the Baseline model's sequential execution of activities, beginning with sub-activity 1.1 (Surveyor locating foundation), the Lean model identified opportunities for concurrent execution of specific sub-activities at this stage. Notably, sub-activities 1.2 (Formwork unloading and preparation) and 3.1 (Rebars cutting and bending) could be undertaken simultaneously with sub-activity 1.1. This parallelization allows successor sub-activities, 1.3 (Framework assembly) and 2 (Plain concrete casting), to potentially start earlier. Furthermore, when combined with sub-activity 3.1, these early starts facilitate an expedited initiation of sub-activity 3.2 (Fabricated rebars movement). Likewise, analyzing the construction sequence further reveals another parallelization opportunity. While foundation activities are ongoing, sub-activity 7.2 (Retaining wall rebars cutting and bending) can be executed concurrently. This enables an immediate start for sub-activity 7.3 (Fabricated rebars movement) upon completion of the retaining wall foundation. Moreover, sub-activity 7.3 can be executed simultaneously with sub-activity 7.1 (Scaffolding installation). Furthermore, an opportunity was found for concurrent execution of sub-activity 6 (Backfilling and compaction) while the retaining wall construction activities are ongoing. Moreover, further sub-activities involving material movement, including 4.1 (Foundation formwork movement) and 8.1 (Retaining wall formwork material), presented opportunities for concurrent execution with other activities throughout the construction process.

As illustrated in (Figure 4-10), this Lean model was developed using ARENA 16.2 software, was subsequently simulated, and its outputs were subjected to a comprehensive comparative analysis with the baseline model. This analysis yielded conclusive findings regarding the impact of implementing the selected Lean tools.

**Table 4-6** Key Lean principles within Developed Lean Models.

| Lean Principle | Application in Simulation Model |
|---|---|
| VA Activities Identification | Measure the efficiency of the process by determining the proportion of time dedicated to activities that directly generate value. |
| Process Improvement: Optmization of Process Flow | Revise the activity sequence to maximize parallelization opportunities with the objective of |

| Lean Principle | Application in Simulation Model |
|---|---|
| | minimizing overall project duration. |
| Operation Improvement:<br>Get Quality Right the First Time | Focus on achieving first-pass quality to eradicate rework |

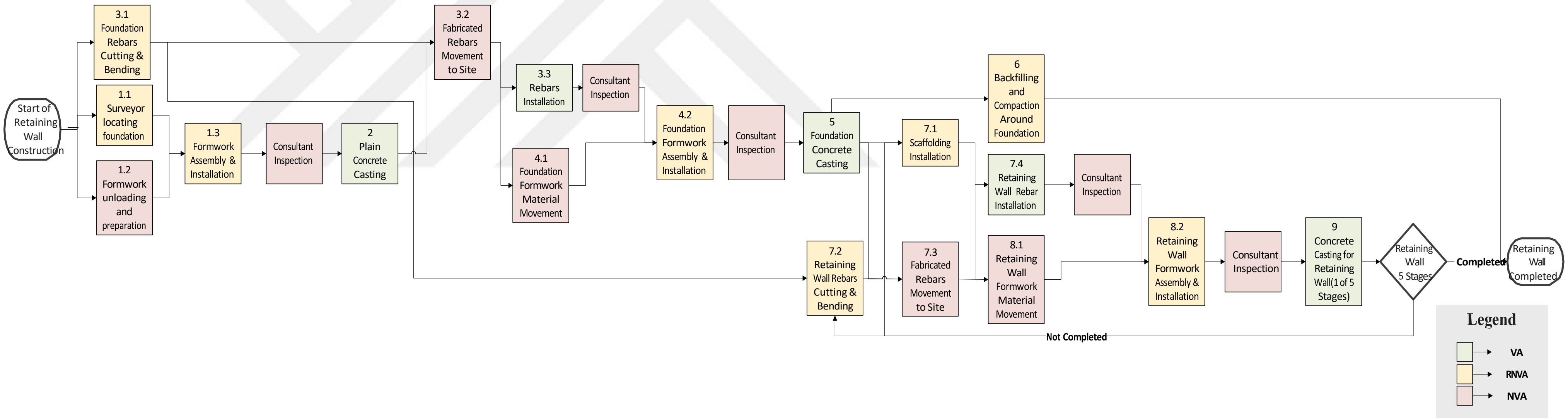



**Figure 4-9** Enhanced Process Map of Case Study Process.

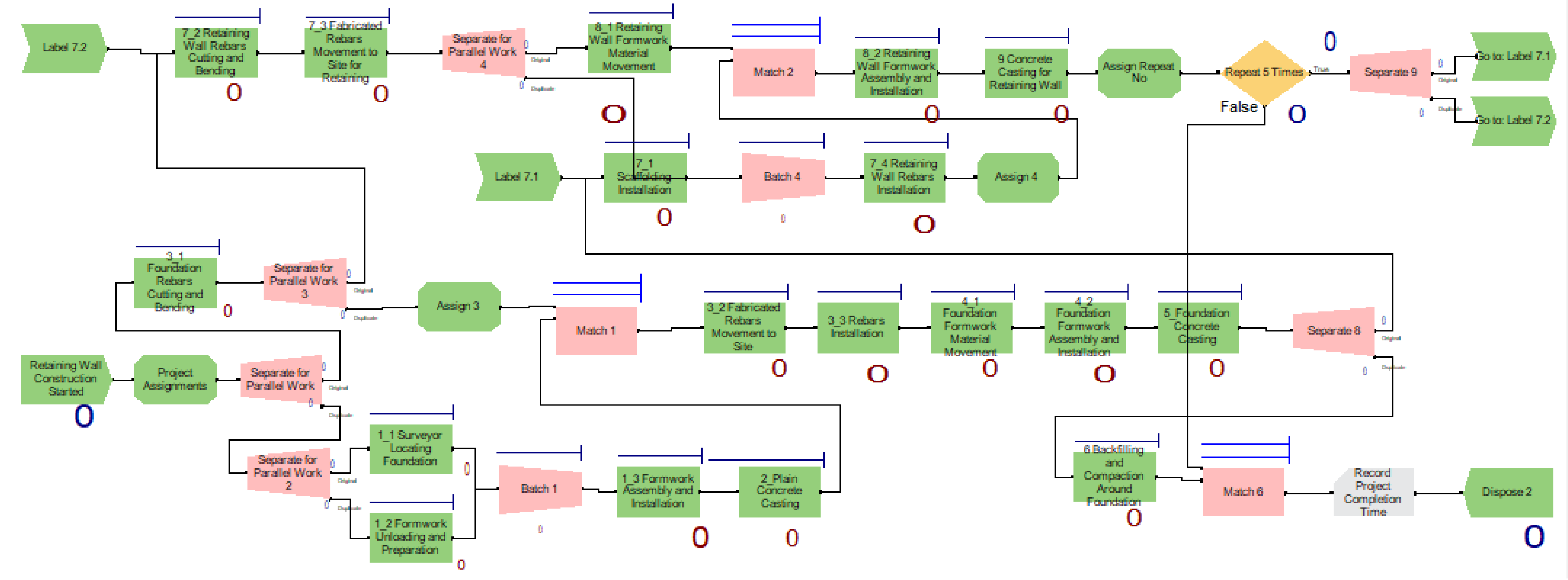



**Figure 4-10** Lean Model in Arena.

## 4.5. Findings Comparative Analysis

### 4.5.1. .. Lean Implementation Analysis

Drawing upon insights from the specific observations of the case study, relevant literature from comparable research, and expert judgment tailored to the site context, this study investigated the efficacy of Lean principles in influencing overall process duration. The impact of Lean implementation on individual activity durations was assessed based on established benchmarks from similar studies and further refined through site-specific expert insights. This approach meticulously analyzed and categorized wastes, subsequently applying targeted Lean techniques. Notably, the improvement process followed four key phases:

(1) Selecting appropriate Lean tools.

(2) Augmenting value-adding activities through alternative methods.

(3) Optimizing required non-value-adding activities.

(4) Eliminating non-value-adding activities where possible.

Based on the above-mentioned phases, four different scenarios were defined for the analysis as shown in (Table 4-7):

**Table 4-7** List of the scenarios developed for the simulation.

| SN | Scenario Definition |
|---|---|
| 1. | **S1:** Base Model or non-lean real-world model |
| 2. | **S2:** The only change with respect to Base model is some of the activities are parallelized as shown in (Figure 4-9) and (Figure 4-10). |
| 3. | **S3:** Beside parallelization, it is assumed that all reworks are eliminated with the application of “Get Quality Right the First Time” principle. |
| 4. | **S4:** Besides parallelization and rework-elimination, with the application of other lean techniques (Table 4-5), it is assumed that certain amount of improvements were attained in activity durations (Table 4-8). |

After running each scenario 100 times, One-way ANOVA was conducted to compare multiple means with a statistically justifiable method. Minitab's Stat>ANOVA>One-Way tool is used in the comparisons due to its flexibility.

**Table 4-8.** Activities Coefficient Comparison and Introduced Improvements.

| Sub-Activity | Non-Lean Parameters [$\mu$, $\sigma$] [$a$, $c$, b] | Lean Parameters [$\mu$, $\sigma$] [$a$, $c$, $b$] | Percent Reduction | |
|---|---|---|---|---|
| | | | Mean | Std.Dev. |
| 1.1 Surveyor locating foundation | [0.58, 0.16] [0.25, 0.5, 1] | [0.53, 0.14] [0.23, 0.45, 0.9] | 8.6% | 12.5% |
| 1.2 Formwork unloading and preparation | [0.5, 0.1] [0.25, 0.5, 0.75] | [0.43, 0.09] [0.22, 0.43, 0.65] | 14.0% | 10.0% |
| 1.3 Plain Concrete Formwork Assembly & Installation | [1, 0.2] [0.5, 1, 1.5] | [0.88, 0.18] [0.44, 0.88, 1.31] | 12.0% | 10.0% |
| Inspection | [1, 0.2] [0.5, 1, 1.5] | [0.81, 0.17] [0.41, 0.81, 1.22] | 13.0% | 15.4% |
| 2. Concrete Casting for Plain Concrete | [0.92, 0.26] [0.25, 1, 1.5] | [0.8, 0.22] [0.22, 0.88, 1.31] | 11.1% | 10.7% |
| 3.1 Foundation Rebars Cutting & Bending | [9, 1.22] [6, 9, 12] | [8, 1.09] [5.33, 8, 10.67] | 16.9% | 19.2% |
| 3.2 Fabricated Rebars Movement to Site | [1.42, 0.26] [0.75, 1.5, 2] | [1.18, 0.21] [0.63, 1.25, 1.67] | 10.0% | 11.0% |
| 3.3 Rebars Installation | [5, 0.82] [3, 5, 7] | [4.5, 0.73] [2.7, 4.5, 6.3] | 12.0% | 10.0% |
| Inspection | [1.17, 0.31] [0.5, 1, 2] | [0.99, 0.26] [0.43, 0.85, 1.7] | 15.0% | 14.5% |
| 4.1 Foundation Formwork Material Movement | [1, 0.2] [0.5, 1, 1.5] | [0.88, 0.18] [0.44, 0.88, 1.31] | 9.6% | 11.1% |
| 4.2 Foundation Formwork Assembly & Installation | [4.67, 0.62] [3, 5, 6] | [3.97, 0.53] [2.55, 4.25, 5.1] | 14.2% | 14.1% |
| Inspection | [1, 0.2] [0.5, 1, 1.5] | [0.81, 0.17] [0.41, 0.81, 1.22] | 10.1% | 10.0% |
| 5. Concrete Casting for Foundation | [1.25, 0.27] [0.75, 1, 2] | [1.13, 0.24] [0.68, 0.9, 1.8] | 16.7% | 16.5% |
| 6. Backfilling and Compaction Around Foundation | [6.33, 0.85] [4, 7, 8] | [5.43, 0.73] [3.43, 6, 6.86] | 13.4% | 12.3% |
| 7.1 Scaffolding Installation | [10.85, 0.7] * [1.5, 2, 3] | [9.75, 0.63] [1.35, 1.8, 2.7] | 10.0% | 10.3% |
| 7.2 Retaining Wall Rebars Cutting & Bending | [15, 0.91] [2, 3, 4] | [12.5, 0.76] [1.67, 2.5, 3.33] | 12.0% | 13.0% |
| 7.3 Fabricated Rebars Movement to Site | [7.1, 0.57] [0.75, 1.5, 2] | [6.15, 0.5] [0.65, 1.3, 1.73] | 12.5% | 12.1% |
| 7.4 Retaining Wall Rebar | [22.5, 1.65] | [20.25, 1.48] | 9.3% | 11.4% |

| Sub-Activity | Non-Lean Parameters $[\mu, \sigma]$ $[a, c, \text{b}]$ | Lean Parameters $[\mu, \sigma]$ $[a, c, b]$ | Percent Reduction | |
|---|---|---|---|---|
| | | | Mean | Std.Dev. |
| Installation | [2.5, 5, 6] | [2.25, 4.5, 5.4] | | |
| Inspection | [5, 0.46] [0.5, 1, 1.5] | [4.4, 0.4] [0.44, 0.88, 1.31] | 19.0% | 15.0% |
| 8.1 Retaining Wall Formwork Material Movement | [20, 0.91] [3, 4, 5] | [17.5, 0.8] [2.626, 3.5, 4.38] | 30.8% | 45.2% |
| 8.2 Retaining Wall Formwork Assembly & Installation | [5.4, 0.35] [0.75, 1, 1.5] | [4.9, 0.31] [0.676, 0.9, 1.35] | 19.0% | 15.0% |
| Inspection | [5, 0.46] [0.5, 1, 1.5] | [4.05, 0.37] [0.41, 0.81, 1.22] | 19.0% | 19.6% |
| 9. Concrete Casting for Retaining Wall (5 Stages) | [5.4, 0.35] [0.75, 1, 1.5] | [4.9, 0.31] [0.68, 0.9, 1.35] | 19.0% | 19.6% |

*Due to the repetition of activities, starting from activity 7.1, mean and Std.Dev. parameters of the activity estimated for 5 repetition, whereas triangular parameters are for single repetition.

(Figure 4-11) shows the individual 95% CIs for each scenario means. As a first impression, addition of each lean technique substantially decreases the project durations. Secondly the widths of the CIs are too small to conclude that the differences are statistically and practically significant. Nevertheless, (Table 4-9) gives the results of the formal hypothesis test, with the null hypothesis claiming all scenario means are equal. Extremely large F-value and resulting p-value (<0.00001) helps us to reject null hypothesis with a great confidence.

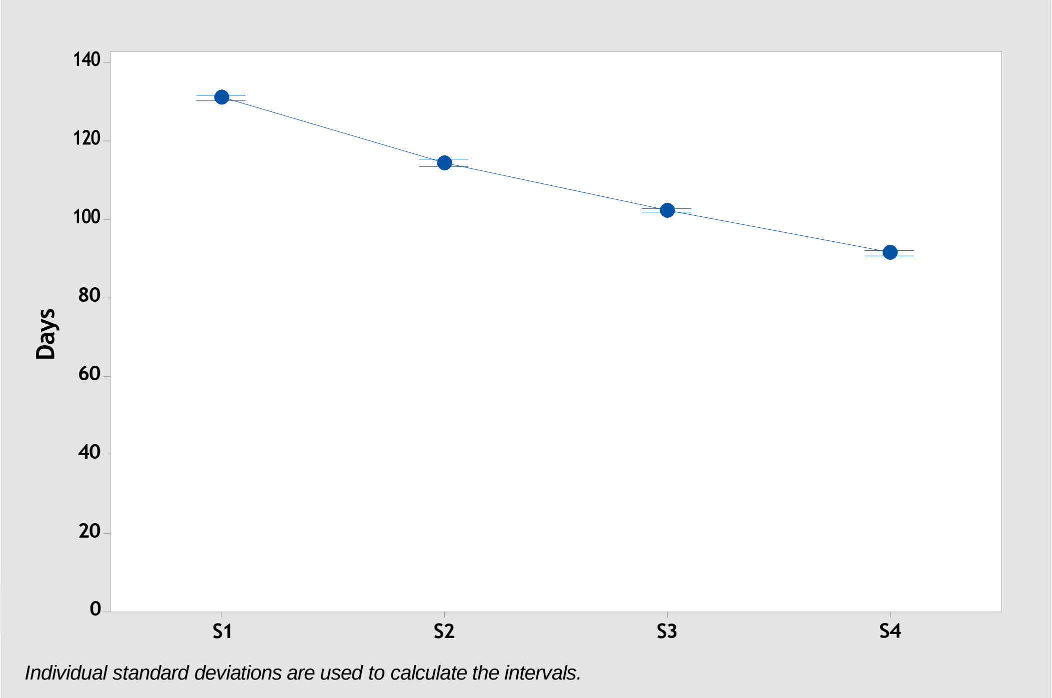



**Figure 4-11.** Individual 95% CIs for the scenario means.

**Table 4-9** ANOVA table for scenarios' mean comparison.

| Analysis of Variance | | | | | |
|---|---|---|---|---|---|
| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
| Factor | 3 | 86,243 | 28,747.7 | 2,425.2 | 0.0000 |
| Error | 396 | 4,694 | 11.9 | | |
| Total | 399 | 90,937 | | | |

Following the ANOVA, Tukey Simultaneous Tests were applied to identify which groups are statistically different than the others. In (Table 4-10), we see that none of the CIs for differences of means for sample pairs includes zero. Hence, we can conclude that we have strong evidence to reject the claim, stating that the means are equal. (Table 4-11) and (Figure 4-12) supports the same conclusion with grouping information and graphical representation of the CIs.

**Table 4-10** Tukey Simultaneous Tests for Differences of Means

| Difference of Levels | Difference of Means | SE of Difference | % CI | T-Value | Adjusted P-Value |
|---|---|---|---|---|---|
| S1 – S2 | 10.899 | 0.487 | (15.532, 18.032) | 34.47 | 0.000 |
| S1 – S3 | 22.792 | 0.487 | (27.425, 29.925) | 58.89 | 0.000 |
| S1 - S4 | 39.574 | 0.487 | (38.324, 40.824) | 81.28 | 0.000 |
| S2 - S3 | 11.893 | 0.487 | (21.542, 24.042) | 46.81 | 0.000 |
| S2 - S4 | 22.792 | 0.487 | (21.542, 24.042) | 46.81 | 0.000 |
| S3 - S4 | 10.899 | 0.487 | (9.649, 12.149) | 22.38 | 0.000 |

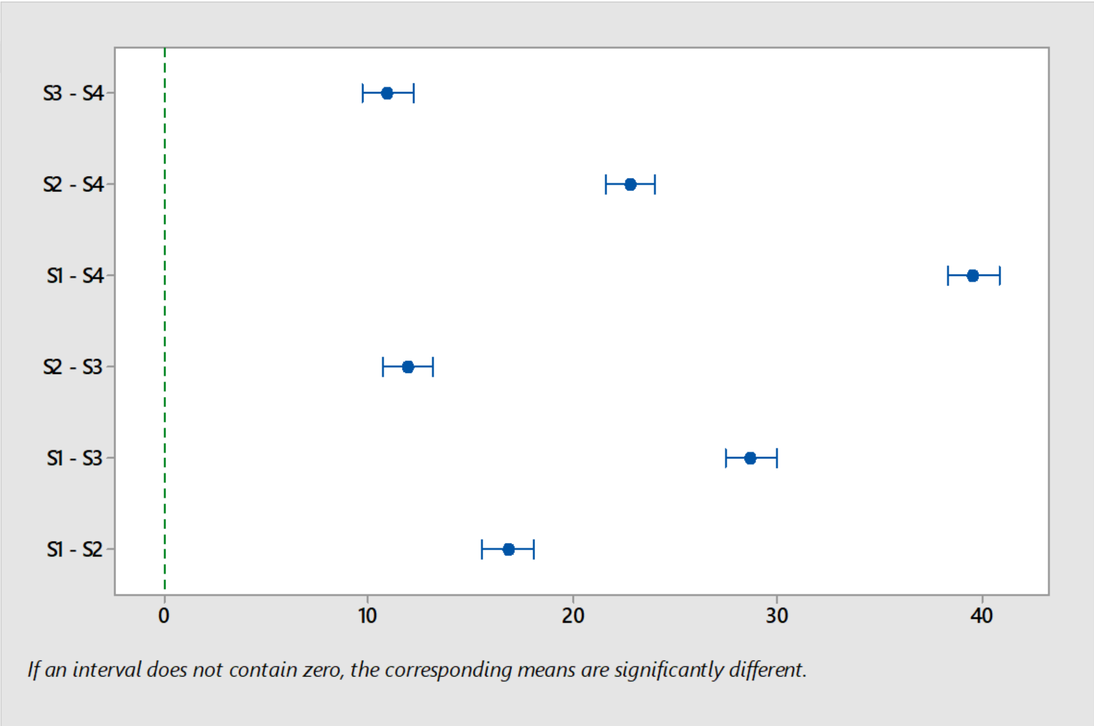



**Figure 4-12** Tukey Simultaneous 95% Cis for Difference of Scenario Means.

**Table 4-11** Grouping Information Using the Tukey Method and 95% Confidence.

| Factor | N | Mean | Grouping | | | |
|---|---|---|---|---|---|---|
| S1 | 100 | 130.652 | A | | | |
| S2 | 100 | 113.870 | | B | | |
| S3 | 100 | 101.977 | | | C | |
| S4 | 100 | 91.077 | | | | D |

*Means that do not share a letter are significantly different.*

The cumulative effects of implementing practical lean applications on the activities within the case study can be analyzed through examining the average values of the coefficients assigned to each activity. These mean values calculated based on the triangular distribution presented in (Table 4-8), reveal a consistent decrease across all activity types in the lean scenario compared to the non-lean scenario.

### 4.5.2. .. Simulation Analysis

The efficacy of employing Lean principles within the construction process is rigorously evaluated through a comparative analysis of baseline and Lean simulation models. Therefore, to achieve statistically significant insights, a comprehensive simulation campaign was conducted, involving 100 replications for both the baseline and lean models. Consequently, the findings presented in this research are based on the average outcomes across these replications. Process total duration and efficiency, as critical performance indicators, are calculated and contrasted between the two models. (Table 4-12) presents a succinct summary of the comparative findings, while subsequent sections offer detailed examinations of each performance measure.

**Table 4-12** Comparison of Performance Measures between Baseline and Lean Models

| Simulation Model | Efficiency (%) | Total Duration (days) | VA (days) |
|---|---|---|---|
| S1 | 26.85% | 130.652 | 35.08 |
| S2 | 30.81% | 113.87 | 35.08 |
| S3 | 34.40% | 101.977 | 35.08 |
| S4 | 34.64% | 91.077 | 31.55 |
| Improvement (%) | 7.79% | 30.29% | |

*Construction Process Total Duration (Cycle Time)*

The effective reduction of cycle times not only facilitates the attainment of timely project completion but also engenders both heightened process efficiency and improved labor productivity as a direct consequence (Abbasian-Hosseini, Nikakhtar, & Ghoddousi, 2014). To assess the impact of lean principles, contrasting cycle times in the baseline and lean simulation models is essential.

As demonstrably illustrated in (Table 4-12) and (Figure 4-15), the integration of Lean construction principles within S1 model yielded a substantial 30.29% reduction in cycle time for the retaining wall construction project. This noteworthy improvement can be attributed to three primary factors, further elucidated in (Figure 4-16): firstly, the optimized process flow in S2 model, facilitated by the initiation of activities in parallel whenever dependencies allowed, thus minimizing wait times, and contributing a 12.84% decrease in cycle time. Secondly, the partial elimination of non-value-adding activities in S3 model, notably through reduced rework achieved via the "Get Quality Right First Time" principle, accounted for an additional 9.10% reduction in cycle time. This combined optimization strategy effectively streamlined the process, enhanced its overall efficiency, and culminated in faster completion times.

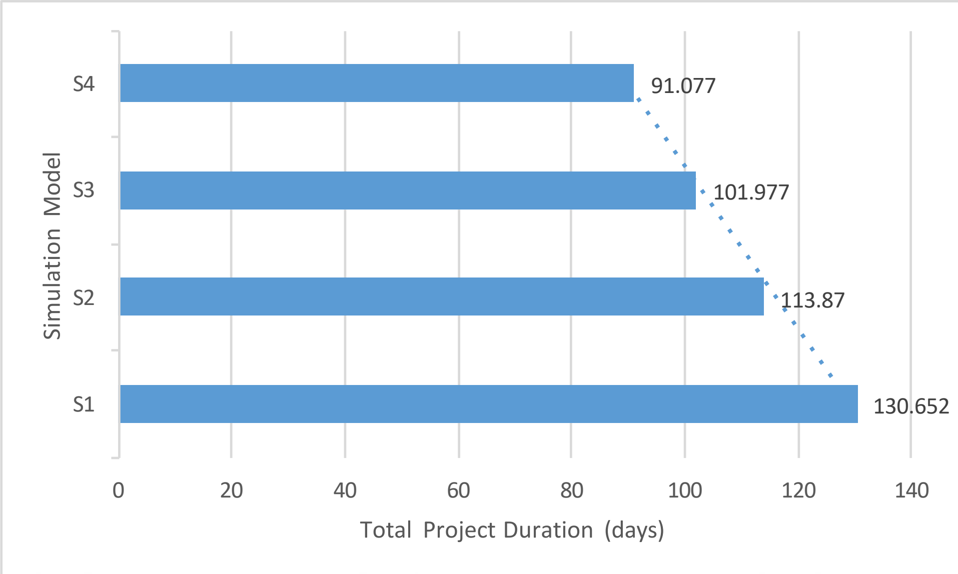



**Figure 4-13** Lean Models Total Project Durations.

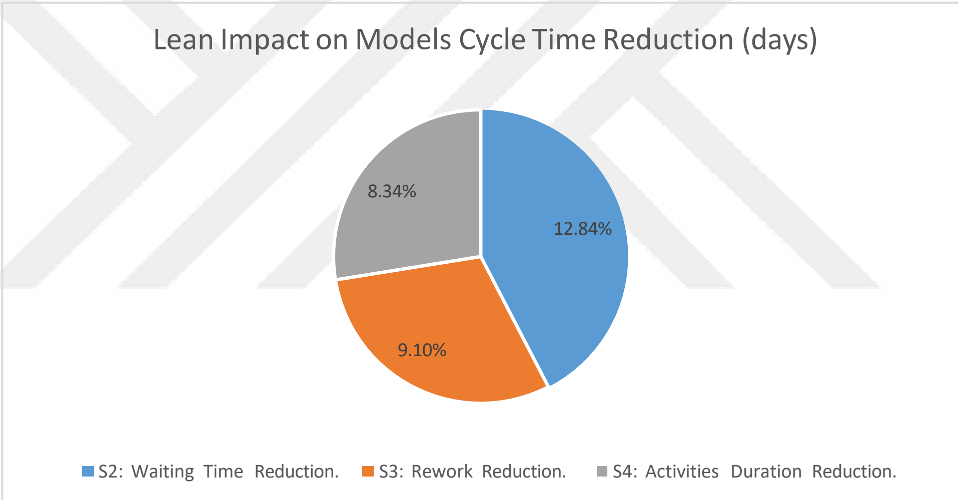



**Figure 4-14** Lean Implementation Impact on Total Cycle Time Reduction.

Thirdly, to further assess the impact of implemented lean construction techniques represented in (Table 4-5), along with proposed process flow modifications illustrated in (Figure 4-9), a comprehensive simulation model S4 was developed. This model incorporated lean duration parameters recommended by experts presented in (Table 4-8) along with the proposed lean principles in (Table 4-6). Subsequently, the simulation was run for 100 iterations. The output of this comprehensive simulation is indicated in (Figure 4-15) and (Figure 4-16) along with previously discussed scenarios. S4 model achieved a significant decrease in project duration, reducing an additional 8.34% of 30.29% total duration reduction compared to the baseline model S1. This translated to a total project time of 91.077 days.

*Construction Process Efficiency*

Among the key performance factors used to evaluate construction processes, efficiency holds paramount importance (Abbasian-Hosseini, Nikakhtar, & Ghoddousi, 2014). Evaluating efficiency within a predefined framework aims to enhance performance by prioritizing value-adding activities and systematically eliminating non-value activities (Diekmann, J.E.; Krewedl, M.; Balonick, J.; Stewart, T.; Won, S., 2004). Thus, this study utilizes a structured process to assess efficiency, with the goal of optimizing performance through focused emphasis on value creation and the proactive elimination of non-value elements.

The Lean simulation models showed an appreciable increase in retaining wall process efficiency from 26.85% to 34.64%, i.e., a remarkable improvement of 7.79%, as demonstrated in (Table 4-12) and (Figure 4-17) The success was achieved by integrating Lean principles into S1 model making it possible to assess process effectiveness, which is now evidently improved. Simulation outputs identified a progressive increase in process efficiency achieved through iterative optimization of the construction process (Figure 4-18). Model S2, characterized by an enhanced flow facilitated by parallel execution whenever feasible, minimized wait times and contributed 3.96% of the total 7.79% improvement. Further efficiency gains were observed in Model S3, where the partial elimination of non-value-adding activities, notably reduced rework enabled by the "Get Quality Right First Time" principle, accounted for an additional 3.59%. Finally, Model S4 incorporated expert-recommended lean duration parameters (Table 4-8) along with previously established Lean principles (Table 4-6), resulting in a further modest improvement of 0.24% in construction process efficiency. although its impact on the project total time reduction was noteworthy.

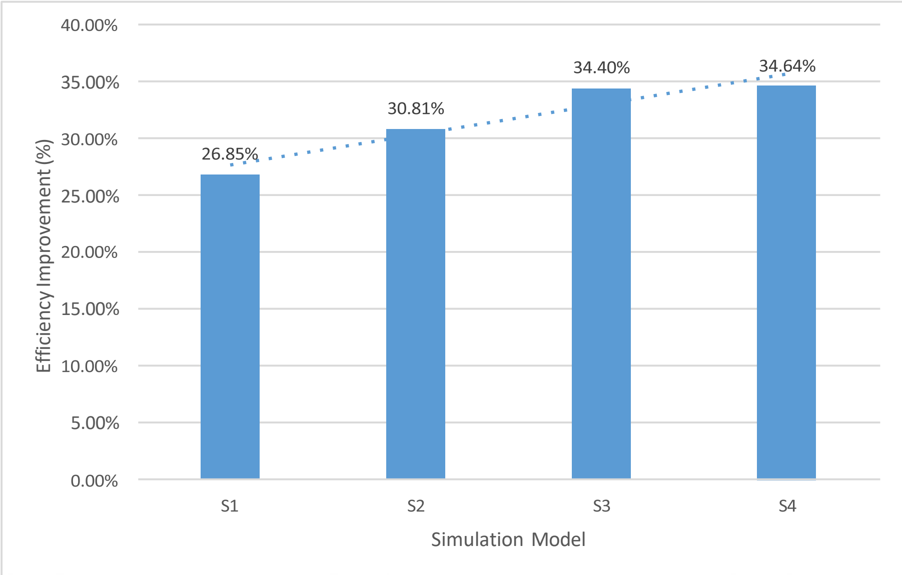



**Figure 4-15** Efficiency Improvement across Simulation Models.

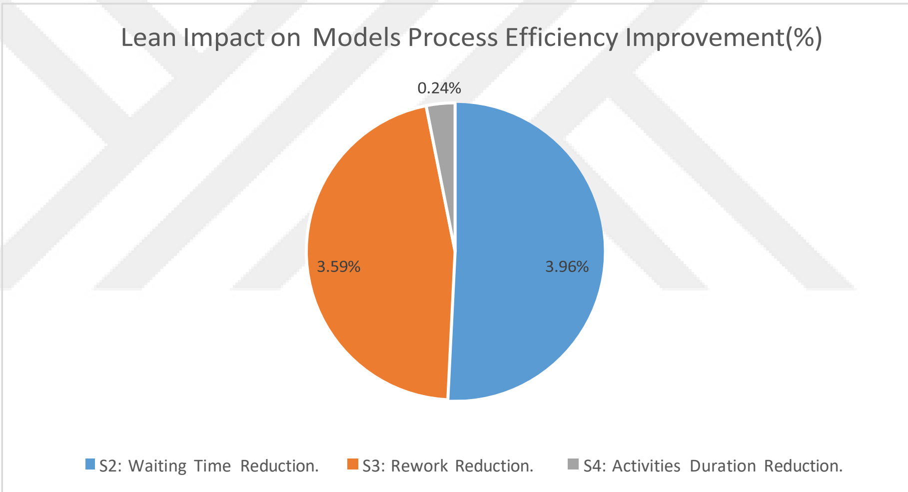



**Figure 4-16** Lean Implementation Impact on Total Efficiency Improvement.

## 5 .. Conclusion

This research examined the effects of Lean construction activities on performance of medium-sized construction projects in Saudi Arabia. The main objective was to create a universal procedure for implementing lean principles in retaining wall construction as a case study. The paper applied simulation modeling using ARENA 16.2 to refine the construction process and generate leaner process models. The study provides important findings that show how Lean is useful in improving project outcomes. For example, application of such key principles as value specification, value stream mapping, value flow, pull production and continuous improvement resulted in remarkable improvements in performance. Specifically, models S2 and S3 demonstrated noteworthy improvements in process efficiency, registering increases of 3.96% and 3.59%, respectively. Concurrently, cycle time reductions for these models were observed, with declines of 12.84% for S2 and 9.10% for S3 for the retaining wall construction process. In addition, further optimization of process and operational aspects reduced project total time thereby concretizing the benefits of a leaner system. In support of broader uptake, this research presents an applicable Lean Construction Framework. This framework equips users with tools and techniques to identify waste, implement lean practices, and optimize existing workflows. Integrating the activity duration parameters derived from its lean implementation into simulation model S4 further enhanced process efficiency by 0.24%, culminating in a total improvement of 7.79%. Additionally, project duration reductions of 8.34% were achieved, bringing the total project time reduction to 30.29%, demonstrating the framework's effectiveness across diverse scenarios. However, this research makes significant contributions through quantifying the benefits of Lean By providing numerical evidence for improved efficiency, it seeks to encourage further uptake of Lean principles within the building sector by offering valuable insights as generated from findings discussed within five main core Lean principles alongside traditional simulation steps which are familiar to building managers who may be able to use them to improve their job skills.

## 5.1. Research Limitation

1 The proposed Lean techniques and tools have neither implemented nor tested actually in the case study project. However, while this raises concerns about their real-world efficacy, simulation remains the most effective approach for quantitatively evaluating their potential impact, which is difficult to implement into the ongoing case study project.

2 While parallelizing some activities in S2 model, the resource capacities were assumed unlimited, which may be unrealistic in real life.

3. Due to data limitations, some parameters within the Lean implemented activities and simulation models were based on estimates provided by construction experts. While not as accurate as historical data, these experts possessed intimate familiarity with the construction site observation and activity duration estimation, ensuring the estimates were as accurate as possible.

4 Due to the varied nature of the observed activities and limited data collection resources, factors such as labor productivity, resource utilization, and cost could not be incorporated into this study.

## 5.2. Contribution and generalizability

This research aimed at reducing wasteful practices targeting major sources of non-value-adding activities and propose relevant approaches to waste reduction. For instance, the presented approach can be used by practitioners who want to evaluate different Lean scenarios and determine their possible implications before they are applied. Although the primary focus is on retaining wall construction, the research demonstrates that Lean principles and simulation are applicable in many other types of construction operations, which may lead to considerable performance improvements in this industry.

In conclusion, this research underscores the benefits of integrating Lean construction principles and simulation modeling towards optimizing construction process performance. The developed framework along with substantive simulation models output analysis findings provide useful resource for practitioners in the industry leading it towards improved efficiency through leaner processes.

# 6 .. REFERENCES


Abbasian-Hosseini, S. A., Nikakhtar, A., & Ghoddousi, P. (2014). Verification of Lean Construction Benefits through Simulation Modeling:A Case Study of Bricklaying Process. *KSCE Journal of Civil Engineering*, 1248-1260.

Abdel-Razek, R. H., Abd Elshakour M, H., & Abdel-Hamid, M. (2007). Labor productivity: Benchmarking and variability in Egyptian projects. *International Journal of Project Management*, 189–197.

Adamu, I., & Howell, G. (2012). APPLYING LAST PLANNER® IN THE NIGERIANCONSTRUCTION INDUSTRY. *Proceedings of the 20th Annual Conference of the International Group for Lean Construction*, (pp. 18-22). SanDiego, CA.

Alarcon, L. F., & Ashley, D. B. (1999). Playing games: evaluating the impact of lean production strategies on project cost and schedule. *Proceedings of the 7th Annual Conference of the International Group for Lean Construction*, (pp. 263–274.). Berkeley, USA,.

AlSehaimi, A. O., Fazenda, P. T., & Koskela, L. (2014). Improving constructionmanagement practice with theLast Planner System: a case study. *Engineering, Construction andArchitectural Management*, 51-64.

Al-Sudairi, A. A. (2007). Evaluating the effect of construction process characteristics to the applicability of lean principles. *Construction Innovation, 1*(7), 99-121.

Altiok, T., & Melamed, B. (2007). *Simulation modeling and analysis with ARENA.* Piscataway,NewJersey: Elsevier.

Arleroth, J., & Kristensson, H. (2011). *Waste in Lean Construction– A case study of a PEAB construction site and the developmentof a Lean Construction Tool.* Göteborg, Sweden: Chalmers University of Technology.

Ayarkwa, J., Agyekum, K., Adinyira, E., & Osei-Asibey, D. (2015). Barriers to successful implementation of Lean Construction in the Ghanaian building industry. *Journal of construction*, 03-11.

Aziz, R., & Hafez, S. (2013). Applying lean thinking in construction and performance improvement. *Alexandria Engineering Journal*, 679-695.

Bajjou, M. S., & Chafi, A. (2018). Lean construction implementationin the Moroccan construction industry: Awareness, benefits and barriers. *Journal of Engineering, Designand Technology, 16*(4), 533-556. doi:10.1108/JEDT-02-2018-0031

Bajjou, M. S., Anas, C., & Ennadi, A. (2017). The Potential Effectiveness of Lean Construction Tools in Promoting Safety on Construction Sites. *International Journal of Engineering Research in Africa*, 179-193.

Bajjou, M., & Chafi, A. (2020). Lean construction andsimulation for performanceimprovement: a case study ofreinforcement process. *International Journal of Productivity and Performance Management*, 459-487.

Banks, J., Carson, I., Nelson, B., & Nicol, D. (2005). *Discrete-event System Simulation.* Pearson.

Bardalai, R., & and Jayakumar, A. (2015). Study and implementation of lean technique in construction industry- A case study. *International Journal of Innovative Research in cience, Engineering and Technology.*, 2277-2286.

Bashir, A., Suresh, S., Oloke, D., Proverbs, D., & Gameson, R. (2015). Overcoming the challenges facing Lean Construction practice in the UK contracting organizations. *International Journal of Architecture, Engineering and Construction.*, 10-18.

Bilagi, A. U., & Vasanthakumara, S. A. (2017). Implementation of Lean Principles in the Manufacturing of GEIS-2. *IUP Journal of Operations Management*, 34 - 52.

Bygballe, L., & Sward, A. (2014). Implementing Lean Construction: A practice perspective. *22nd Annual Conference of the International Group for Lean Construction* (pp. 3-14). Oslo, Norway: IGLC.

Cano, S., Delgado, J., Botero, L., & Rubiano, O. (2015). Barriers and success factors in Lean Construction implementation: survey in pilot context. *Proc. 23rd*

*Ann. Conf. of the Int'l. Group for Lean Construction.* (pp. 631-641). Perth, Australia: The International Group for Lean Construction.

Chiarini, A., Baccarani, C., & Mascherpa, V. (2018). Lean production, ToyotaProduction System andKaizen philosophy: A conceptual analysis from theperspective of Zen Buddhism. *The TQM Journal*. doi:10.1108/TQM-12-2017-0178

Dave, B., Koskela, L. J., Kiviniemi, A., & Tzortzopoulos, P. (2013). *Implementing lean in construction : lean construction and BIM.* London: CIRIA.

Demirkesen, S. (2020). Measuring impact of Lean implementation onconstruction safety performance: a structuralequation model. *Production Planning & Control*, 412-433.

Diekmann, J.E.; Krewedl, M.; Balonick, J.; Stewart, T.; Won, S. (2004). *Application of Lean Manufacturing Principles to Construction.* Austin, Texas: The Construction Industry Institute, The University.

El-Sawalhi, N. I., Jaber, B. M., & Al Shukri, A. (2018). Towards lean and green thinking in constructionprojects at Gaza Strip. *Organization, Technology and Management in Construction*, 1827–1838.

Enshassi, A., Abo Elaish, R., & Arain, F. (2018). Barriers of Lean Tools Implementation to Eliminate Construction Waste. *International Journal of Construction Project Management, 10*(2), 123 - 136. Retrieved January 2023

Eriksson, P. E. (2010). Improving construction supply chain collaboration and performance: a lean construction pilot project. *Supply Chain Management*, 394-403.

Erol, H., Dikmen, I., & Birgonul, M. (2017). Measuring The Impact of Lean Construction Practices on project Duration and Variability: A Simulation-Based Study on Residential Buildings. *Journal of Civil Engineering and Management*, 241 - 251.

Farrar, J., AbouRizk, S., & Mao, X. (2004). Generic implementation of lean concepts in simulation Models. *Lean Construction Journal*, 1-23.

Garrett, D. F., & Lee, J. (2011). Lean Construction SubmittalProcess—A Case Study. *Quality Engineering*, 84-93.

Hajdu, M., & Bokor, O. (2016). Sensitivity analysis in PERT networks: does activity duration distribution matter. *Automation in Construction, 65*, 1-8. doi:https://doi.org/10.1016/j.autcon.2016.01.003.

Issa, H. (2013). Implementation of lean construction techniquesfor minimizing the risks effect on project construction time. *Alexandria Engineering Journal*, 697-704.

Issa, U. H., & Alqurashi, M. (2020). A Model For Evaluating Causes Of Wastes And Leanimplementation In Construction Projects. *Journal of Civil Engineering and Management*, 331–342.

Kadarova, J., & Demeckoa, M. (2016). New approaches in Lean Management. *3rd Global Conference On Business, Economics, Management And Tourism* (pp. 11-16). Rome, Italy: Procedia Economics and Finance.

Koskela, L. (1992). *Application of new production theory in construction.* Stanford, USA: Stanford University.

Koskela, L. (1993). Lean Production in Construction. *Proceedings of the 10th ISARC* (pp. 47-54). Houston, USA: IAARC.

Koskela, L. (2000). *An exploration towardsa production theory andits application to construction.* ESPOO: Technical Research Centre Of Finland.

Koskela, L., Howell, G., Ballard, G., & Tommelein, I. (2002, December 24). The foundations of lean construction. *Design and construction: Building in value, 291*, 211-226. Retrieved from Research Gate: https://www.researchgate.net/publication/28578914_The_foundations_of_lean_construction

Krupka, D., Joseph, A., & Compton, W. (1992). Time as a Primary System Metric. *The National Academies Press, Washington*, 166-172.

Makwana, A. D., & Patange, G. S. (2021). A methodical literature review on application of Lean & Six Sigma in variousindustries. *Australian Journal Of*

*Mechanical Engineering*, 107-121. doi:https://doi.org/10.1080/14484846.2019.1585225

Mao, X., & Zhang, X. (2008). Construction process reengineering by integrating lean principles and computer simulation techniques. *Journal of Construction Engineering and Management* , 371–381.

Marhani, A., Jaapar, A., Bari, N., & Zawawi, M. (2013). Sustainability through lean construction approach: a literature review. . *Procedia-Social and Behavioral Sciences*, 90-99.

Martinez, E., Reid, C. K., & Tommelein, I. D. (2019). Lean construction for affordablehousing: a case study inLatin America. *Construction Innovation*, 570-593.

Maunzagona, S. (2017). “The Impact of Lean on the mining industry: a simulation evaluation approach. *INCOSE International Symposium*, 965-981.

Morgan, J., & Coci, L. (2012). *Recommended Practices for the Application of LEAN Construction Methods to Building New Australian LNG Capacity.* Engineers Australia.

Mossman, A. (2012). *Last Planner- collaborative short-term production planning.* UK: Alan Mossman.

Mostafa, S., Dumrak, J., & Soltan, H. (2013). A framework for lean manufacturing implementation. *Production & Manufacturing Research*, 44-64. doi:https://doi.org/10.1080/21693277.2013.862159

Nahmens, I., & Ikuma, L. H. (2012). Effects of Lean Construction on Sustainabilityof Modular Homebuilding. *Journal of Architectural Engineering*, 155-164.

Norona, M. I., & Mendoza, A. C. (2020). Modular Technology Adaptation to the Horizontal Construction in the Philippines:A Lean Approach. *IEEE 7th International Conference on Industrial Engineering and Applications*, (pp. 355-361). Bangkok, Thailand.

NOWOTARSKI, P., & PASŁAWSKI, J. (2018). Lean management in small and medium-sized constructionenterprises in Poland – selected results. *Scientific*

*Review Engineering and Environmental Sciences, 27*(3), 260-268. doi:10.22630/PNIKS.2018.27.3.25

Nowotarskia, P., Paslawskia, J., & Matyjaa, J. (2016). Improving Construction Processes Using Lean ManagementMethodologies – Cost Case Study. *Procedia Engineering*, 1037 – 1042.

O'Connor, R., & Swain, B. (2013). *Implementing Lean in construction: Lean tools and techniques – an introduction.* London: CIRIA.

Ogunbiyi, O. (2014). *Implementation of the lean approach in sustainable construction: A conceptual framework.* United Kingdom: Doctoral thesis, University of Central Lancashire.

Ogunbiyi, O., Oladapo, A., & Goulding, J. (2013). A Review of Lean Concept and its Application to Sustainable Construction in the UK. *International Journal of Sustainable Construction Engineering and Technology*, 82-92.

Ogunbiyi, O., Oladapo, A., & Goulding, J. (2014). An empirical study of theimpact of lean constructiontechniques on sustainableconstruction in the UK. *Construction Innovation*, 88-107. doi:10.1108/CI-08-2012-0045

Oguntona, O., Aigbavboa, C., & Mulongo, G. (2019). *n Assessment of Lean Construction Practices in the Construction Industry.* Johannesburg, South Africa: Springer International Publishing AG.

Ohno, T. (1988). *Toyota production system.* Boca Raton, Florida: Taylor & Francis Group.

Raghavan, N., Kalidindi, S., Mahalingam, A., Varghese, K., & Ayesha, A. (2014). Implementing lean concepts on Indian Construction Sites: Organisational aspects and lessons learned. *Annual Conference of the International Group for Lean Construction.* (pp. 1181-1190.). Oslo, Norway: IGLC-22,.

Rebaiaia, M. L., & Vieira, D. R. (2014). Integrating PMBOX Standards, Lean and Agile Methods in Project Management Activities. *International Journal of Computer Applications*, 40-46.

Robinson, S., Radnor, Z., Burgess, N., & Worthington, C. (2012). SimLean: utilising simulation in the implementation of lean in healthcare. *uropean Journal of Operational Research,*, 188-197.

Sacks, R., Esquenazi, A., & Goldin, M. (2007). LEAPCON: Simulation of lean construction of high-rise apartment buildings,. *Journal of Construction Engineering and Management* , 529–539.

Sacks, R., Koskela, L., Dave, B. A., & Owen, R. (2010). Interaction of Lean and Building Information Modeling in Construction. *Journal of Construction Engineering and Management*, 968-980.

Sacks, R., Treckmann, M., & Rozenfeld, O. (2009). Visualization of Work Flow to Support Lean Construction. *Journal of Construction Engineering and Management*, 1307-1315.

Salem, O. M., Solomon, J., Genaidy, A., & Minkarah, I. (2006). Lean Construction: From Theory to Implementation. *Journal of Management in Engineering*, 168-175.

Samaila, A., & Adul Hamid, R. (2012). Lean construction techniques implementation in nigeria construction industry. *Canadian Journal on Environmental, Construction and Civil Engineering*, 186-193.

Sarhan, S., & and Fox, A. (2012). Trends and challenges to the development of a lean culture among UK construction organizations. *Proceedings for the 20th Annual Conference of the International Group for Lean Construction* (pp. 18-20). San Diego, USA,: CORE.

Shang, G., & Sui Pheng, L. (2014). Barriers to lean implementation in the construction industry in China. *Journal of Technology Management in China.*, 155-173.

Shehata, M. E., & El-Gohary, K. M. (2011). Towards improving construction labor productivity and projects' performance. *Alexandria Engineering Journal*, 321-330.

Skinnarland, S., & Yndesdal, S. (2014). Barriers to a continuous learning. *22nd Annual Conference of the International Group for Lean Construction* (pp. 1191-1201). Oslo, Norway.: IGLC.

Small, E., Al Hamouri, K., & Al Hamouri, H. (2017). Examination of Opportunities for Integration of Lean Principles in Construction in Dubai. . *Procedia Engineering*, 616-621.

Swefie, M. G. (2021). *Improving project performance using lean construction in Egypt: a proposed framework. [Thesis, the American University in Cairo]*. Cairo: AUC Knowledge Fountain. .

Takus, D. A., & Profozich, D. M. (1997). ARENA software tutorial. *Winter Simulation Conference*, (pp. 541-544). Piscataway, N.J.

Thomas, H. R., Horman, M. J., Minchin, R. E., & Chen, D. (2003). Improving Labor Flow Reliability for Better Productivity as Lean Construction Principle. *Journal of Construction Engineering and Management*, 251-261.

Tserng, H. P., Yin, S. Y.-L., & Ngo, T. L. (2013). A Lean Prebid Planning Model For Construction Contractors: A Case Study In Vietnam. *Journal Of Marine Science And Technology-Taiwan*, 430-441.

Van der Merwe, K. (2017). A longitudinal study of the efficacy of lean learning experienced througha simulated working environment (SWE). *International Journal Of Productivity Andperformance Management*, International Journal of Productivity andPerformance Management.

Vieira, A., & Cachadinha, N. (2011). Lean construction and sustainability-complementary paradigms-a case study. *19th Annual Conference of the International Group for Lean Construction* (pp. 584-594). Lima, Peru.: IGLC.

Wandahl, S. (2014). Lean construction with or without lean–Challenges of implementing lean construction. *Proceedings of the 22nd Annual Conference of the International Group for Lean Construction.* (pp. 97-108). Oslo, Norway: IGLC 22.

Wang, P., Mohamed, Y., A. S., Asce, M., & Rawa, A. (2009). Flow production of pipespool Fabrication: simulation to support implementation of lean technique. *Journal ofConstruction Engineering and Management*, 1027-1038.

Wing, C. (1995). The validity of the triangular distribution assumption in Monte Carlo simulation of construction costs: empirical evidence from Hong Kong. *Construction Management and Economics*, 15-21.

Womack, J. J. (1991). *The Machine that Changed the World: The.* New York: 1st Harper Perennial Ed. .

Womack, J., & Jones, D. (1996). *Lean Thinking.* New York: Simon & Schuster.

Wu, X., Zhao, W., Ma, T., & Yang, Z. (2019). Improving the Efficiency of Highway ConstructionProject Management Using Lean Management. *Sustainability*.

Xing, W., Hao, J. L., Qian, L., Tam, V. W., & Sikora, K. S. (2021). Implementing lean construction techniques and managementmethods in Chinese projects: A case study in Suzhou, China. *Journal of Cleaner Production*, 1-13.

Yang, I.-T. (2005). ‘Impact of budget uncertainty on project time-cost tradeoff. *IEEE Transactions on Engineering Management*, *52*(2), 67 - 174. doi:10.1109/TEM.2005.844924

Yong-Woo, K., & Jinwoo, B. (2010). Assessing the Environmental Impacts of a Lean Supply System: Case Study of High-Rise Condominium Construction in Korea. *Journal of Architectural Engineering*, 144-150.