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Impact of Adopting Lean Principles on Construction Waste in Developing Countries

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Abstract: Construction projects in developing countries often face challenges related to inefficient practices and high levels of waste, leading to cost overruns, delays, and environmental degradation. Lean construction principles have gained attention as a systematic approach to minimize waste and improve efficiency in construction projects worldwide. However, the impact of adopting lean principles on waste reduction in developing country contexts remains a subject that requires investigation. This case study aims to examine how implementing lean construction principles can reduce waste in building projects in developing nations. The research utilizes a mixed-method approach (qualitative and quantitative). Qualitative interviews are conducted with key stakeholders, including project managers, contractors, and architects, to gather their perceptions of the most common type of waste in the construction process and how the lean principle implementation minimizes waste. Quantitative approach: a case study was conducted using a lean simulation model by ARENA software, to measure the impact of lean construction principles on the overall performance of the construction (reinforcement process). One of the key findings in the case study is that the lean model enhances the overall efficiency of processes by eliminating non-value-added activities, standardizing work procedures, and fostering continuous improvement. These practices lead to a reduction in wasted resources, such as the reinforcement process (improvement in overall cutting process by 67.1% and in bending process by 21%) and enhance work productivity by 19.6%, and thus refinement in the overall time cycle by 24.5%. In summary, by adopting lean principles, businesses can create a more sustainable and efficient future while contributing to the overall preservation of natural resources and the environment by focusing on value-added processes.

1. Background

The construction industry positively influences economic growth in both developing and developed countries, the specific dynamics and challenges differ based on the economic context and stage of development [1, 2]. This growth has contributed significantly to waste generation [3, 4, 5], which has become a serious problem, as it impacts the economic dynamics and has an important effect on the environment [6]. Several previous studies indicate that waste emerges during the planning, design, procurement, and construction stages [7, 8, 9].

Construction waste is generally classified into physical waste and nonphysical waste as shown in Figure 1 [10]. Physical wastes related to the materials generated during the process of execution of the projects such as (Steel reinforcement, Bricks, Concrete, Aggregate, Sand, Polystyrene foam, Rockwool, Plastic, Wood, Metal, and water….), whereas nonphysical wastes related to defects (errors), delays, over-processing, over-production, excess inventory, unnecessary transport and conveyance of materials and equipment, and unnecessary motions and movement of people for a construction project. [10, 11].

1.1 Waste categorization in construction projects

- Extensive research in the realm of construction waste has been carried out in recent years, leading to the identification of three distinct categories [12]. These categories encompass (1) direct conversion waste, which pertains to materials, labor, and equipment; (2) noncontributory time wastes, also known as "non-value-added" or simply "waste," refer to activities or processes that do not add value to the end product or service from the customer's perspective, for example (waiting time, unnecessary movement or transportation, excess inventory, overproduction and unnecessary processing steps), (3) contributory time wastes, known as “value-added” refer to activities or processes that contribute value to the end product or service which encompass transportation, inspection, supervision, and communication for instruction [13, 14, 15]. Hence, the investigation has shed light on these professional classifications of construction waste.

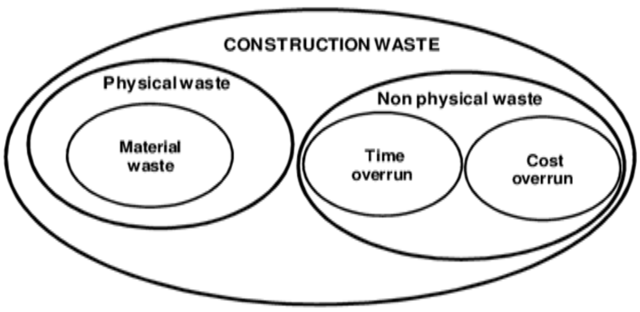

Figure 1. Classification of construction waste [10]

These categories include eight types of waste [16, 17, 18, 19]:

1. Excessive production: Overproduction occurs when more materials, workers, or equipment are utilized than necessary to fulfill customer demands, resulting in an unnecessary surplus of goods.
2. Unnecessary transportation: Inefficient workflows involve the movement of work-in-progress, finished products, or parts over long distances between workstations without true value-added activities.
3. Avoidable motion: Any unnecessary movement performed by employees as part of their daily work, such as searching for tools or stacking items, as well as excessive walking, can be considered wasteful.
4. Excess inventory: Having surplus materials, work in progress, or finished goods at any stage of the production process leads to additional costs associated with storage, transport, and potential obsolescence.
5. Waiting: Delays due to shortages of labor, materials, information, equipment, or bottlenecks result in wasted time and hinder the ability to complete tasks promptly.
6. Defects: The inspection, production, repair, replacement, or disposal of defective products or parts consumes valuable resources and adds unnecessary costs to a project.
7. Over-processing: Inefficient processes that result in either inadequate or excessive levels of quality are considered wasteful and do not provide additional value to the end product.
8. Underutilization of employee creativity: Failing to harness the full potential of staff, disregarding their skills, ideas, and opportunities for improvement, represents a significant waste for businesses.

Thus, efforts to eliminate waste in construction are critical to improve the efficiency, effectiveness, and profitability of construction projects. Therefore, companies need to adopt Lean principles and tools that enable them to identify, measure, and eliminate waste in all aspects of the construction process. Lean management can improve construction project productivity by reducing waste through an effective management approach to overcome the prevalent issues related to waste generation, meeting customer requirements, and accelerating the progress of construction processes [20].

According to the principles of lean manufacturing, the various tasks involved in each production cycle, starting from the initial idea to the final delivery, can be categorized into three main groups: value-adding activities (VA), non-value-adding but necessary activities (NVAR), and non-value-adding activities (NVA). Value-adding activities refer to tasks that contribute to creating value by modifying materials or information to meet the customer's requirements. On the other hand, NVAR activities can be further classified into three subcategories necessary for the construction process: inspection, material positioning, and temporary work and support activities (TWSA), which do not have a lasting impact on the end product. Lastly, non-value-adding activities are those that consume resources, time, or space without making a meaningful contribution to the creation of the product or service required by the customer

1.2 Computer simulation and lean construction

Lean construction aims to enhance the performance of the construction processes by eliminating waste and improving quality (17). According to Van der Merwe (21) and Wang et al. (22), simulation modeling is the most effective way to test the impact of lean construction principles on construction processes before physical implementation.

A review of previous works also shows that computer simulation has emerged as a successful and powerful tool for modeling and analyzing the applicability of lean construction concepts in construction processes [23,24,25,26,27,28,;]. For instance, Halpin and Kueckmann [29] demonstrated that the combination of lean construction and computer simulation provides very impressive operational gains in construction processes such as concrete forming and wall erection. Based on a simulation-based approach, Wang et al. [30] applied flow production and lean construction principles to a pipe spool shop fabrication and, as a result, improved the production performance. Mao and Zhang [31] developed a framework for construction process reengineering that integrates computer simulation and lean principles techniques. Abbasian-Hosseini et al. [24] evaluated lean construction benefits using simulation techniques for a bricklaying process. The results were very significant; a 27% increase in operational efficiency; a 41% decrease in cycle time, and a 43% increase in productivity. Bamana [27] tested how just-in-time, a key tool of lean construction, can be applied in wood construction through simulation. The best scenario allowed for shortening the total construction time from 26.09 to 22.31 weeks, as well as reducing the risk of downtime and increasing the workers’ utilization rate. With the advance of computer science in graphical technologies, there is a growing tendency to work with graphical methods for model development and process simulation (21). ARENA is discrete event simulation (DES) software based on the SIMAN language with a powerful and advanced 3D graphical interface [28].

In general, ARENA helps in modeling uncertainties related to duration and timing, resource allocation, quantity, and flow network. For these reasons, ARENA V.14 is adopted for simulation in this work.

The integration of simulation allows for a dynamic analysis of the construction process, providing valuable insights for practitioners and contributing to the body of knowledge in lean construction. Therefore the current study aimed to evaluate the impact of implementing lean principles and techniques to minimize waste in construction projects while enhancing project productivity. Using the ARENA model software for a case study provides a structured and simulation-based approach to analyze the dynamics of the construction process.

2. Methodology:

This study consists of two main phases through qualitative and quantitative methods as shown in the flow chart (Figure 2). In the first phase, previous research was conducted as a pilot observational study exploring the perceived benefits and challenges among Egyptian construction specialists and experts as well as awareness and adoption of lean principles through a questionnaire including the common types of waste in the industrial construction field, the direct benefits of applying lean construction principles, and the correlations between different items of waste and the overall benefits. The number of participants was 133 out of 149, convenience sampling for the pilot study was used due to its exploratory nature (characteristics of the study group are shown in Figure (3,4)). Also, internal reliability testing using Cronbach's alpha was done to assess the appropriateness of driving conclusions based on the information provided by the questionnaire. The results indicate good reliability for most domains including waste reduction and direct benefits (α=0.86 and 0.73). Reliability was accepted if the estimated Cronbach alpha $\geq$ 0.7). Based on the previous study analysis a case study was conducted using a lean simulation model by ARENA software as a second phase, to measure the impact of lean construction principles on the overall performance of the construction (reinforcement process)

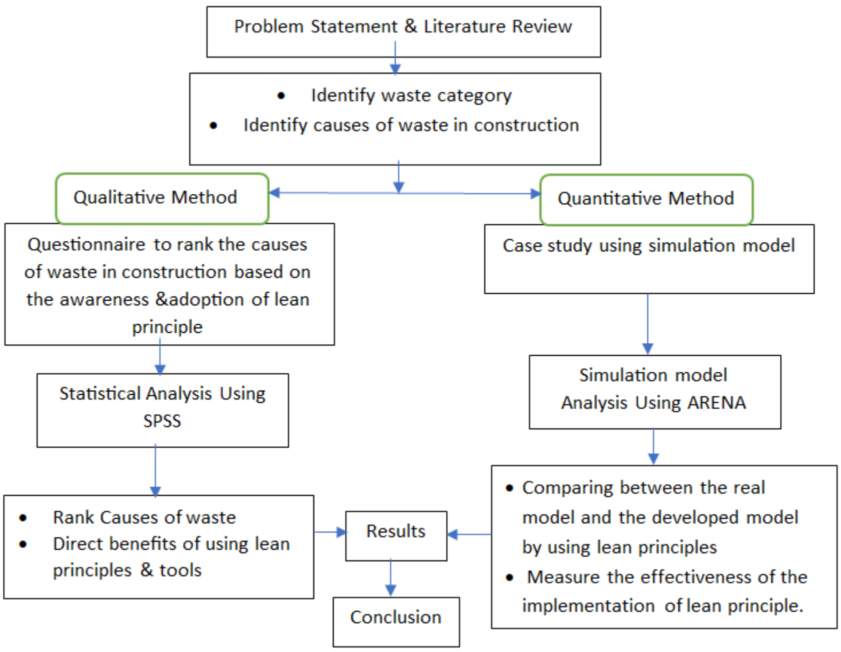

Figure (2): The schematic diagram of the methodology

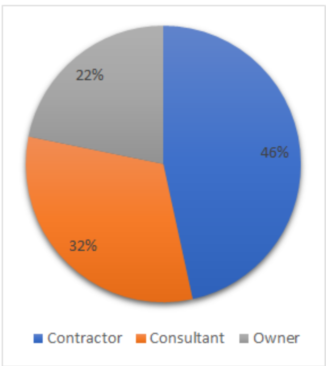

Figure (3): Respondent's Field of work

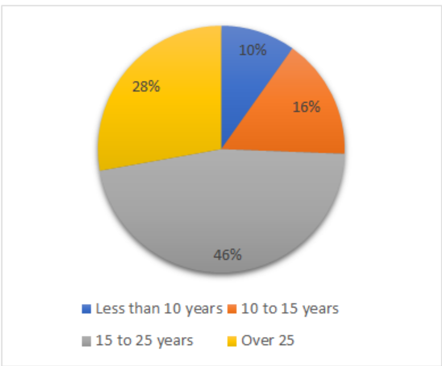

Figure (4): Respondent's years of Experience

3. Analysis

3.1 First phase: Qualitative method

- Utilizing the knowledge acquired from previous research endeavors, it's evident that the construction industry grapples with various types of waste, as highlighted in Figure (5). The preeminent form of waste identified is defects waste (with 22% of the responses), stemming from factors like design miscoordination, evolving customer preferences, and shortcomings in both labor force expertise and site management. Subsequently, the second most prevalent waste pertains to construction project delays (with 18% of the responses), while the third spot is occupied by inventory waste (with 15% of the responses), primarily linked to storage issues. These findings underscore the multifaceted challenges in waste management within the construction sector, emphasizing the need for targeted strategies to address these issues and optimize overall project efficiency.
- As depicted in Figure (6), survey participants assigned rankings to the tangible advantages of implementing lean principles and techniques. Notably, 88 out of 133 respondents concurred that lean construction stands as a highly effective method for enhancing project quality. Additionally, 80 out of 133 respondents asserted its substantial influence on reducing construction costs, while 63 out 133 respondents acknowledged that the application of lean principles can lead to a reduction in construction duration. The results are relevant to other research discussing the benefits of lean principles implementation and matching the common sense that the higher level of adoption will increase the perception of lean construction implementation benefits recognition.
- The correlations between various waste reduction items and the overall benefits are summarized in Figure (7). The darker the blue circles, the higher the magnitude of correlations. Numbers within the circles represent correlation coefficients calculated using the Spearman correlation test. The correlations among the identified waste types exhibit distinctive patterns. The correlation coefficient of 0.74 between waiting waste and over-processing waste denotes a robust and positive linear relationship. This suggests that as waiting waste increases or decreases, there is a corresponding notable increase or decrease in over-processing waste, reflecting a closely linked dynamic between the two variables.

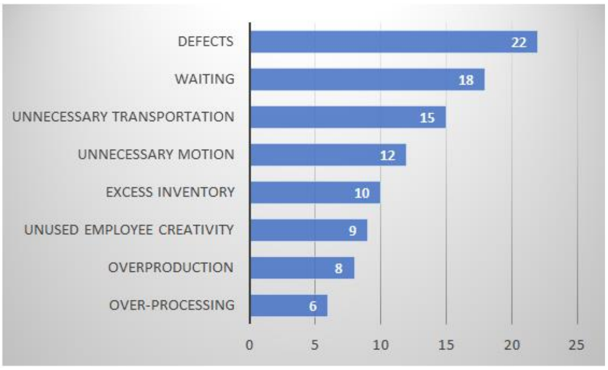

Figure 5: Ranking of waste sources

Figure 6: Ranking of direct benefits of applying lean

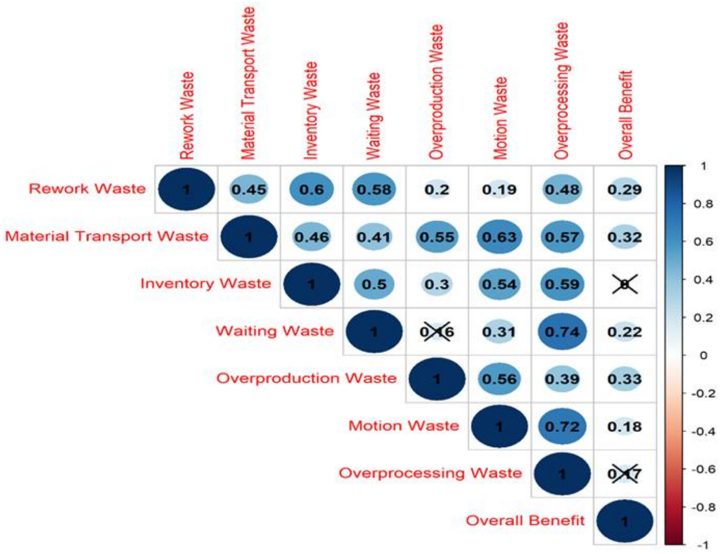

Figure 7: Heat-map summarizing the correlations between different items of waste reduction and the overall benefit

3.2 Phase Two: Quantitative method "Case Study Description"

A case study was conducted on a residential project located in West Cairo, Egypt. For the confidentiality of the project data, only the scope of the project and components would be illustrated herein under without any details about the project's real participants. The project consists of 15 buildings (including 14 multi-family houses and one Boutique Hotel). The Total compound area is 45,000 sqm, consisting of a basement (for all the land area) + Ground + 4 floors. The methodology of the case study is shown in Figure (8).

3.2.1 Field study

This case study is based on on-site observations and interviews with project managers, construction managers, planning engineers, site engineers, and foremen, the result of this process is shown in Figure (9) and Table (1), so we can divide the scope of this stage as follows:

- Value Identification: In order to simplify the process of analyzing and determining the value created at the operational level, the team involved in the project conducted interviews to identify activities that add value (VA) and those that do not (NVA). Their expertise and understanding of customer needs played a crucial role in this assessment.
- Value Stream Mapping: The team also developed a comprehensive flow diagram of the reinforcement process, taking into account input from field observations and discussions with practitioners. This visual representation of the value stream of the final product proved valuable in the development of simulation models.
- Data Collection: To accurately record the time taken for each task in the basement column reinforcement process, involving dimensions of 50X50, specific stirrup shapes with Φ10 (3T10-150), and the main reinforcement Φ16 (12T16), the planning engineer, site engineer, and supervisor participated in data collection. Durations for each step were meticulously measured and collected to ensure the reliability of the input data for the simulation model. Probability distribution fitting was carried out using software packages like Easy Fit and cross-checked manually using the input analyzer from the Arena simulation program Ver 14.00, as outlined in Table (2).

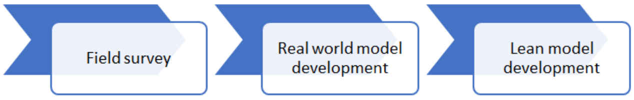

Figure (8): The schematic diagram of the methodology of the case study

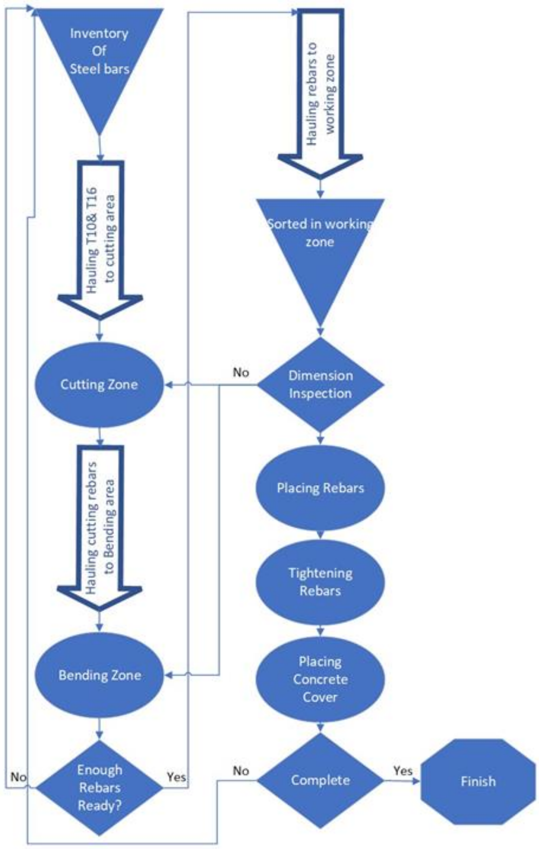

Figure (9): Process Map of reinforcement process

Table 1: Attributes of Process Steps.

Process	Labors	Nature of activity	Classification
Hauling T16	Labor 1	Transportation	NVA
Hauling T10	Labor 2	Transportation	NVA
Cutting for T10&T16	Labor 3	Operation	VA
Hauling T10 to bending	Labor 2	Transportation	NVA
Bending for T10	Labor 4	Operation	VA
Hauling T16 &T10 to working Zone	Labor 1&2	Transportation	NVA
Rework	Forman & Labor 4	Rework	NVA
Installation (Placing RFT., Tightening and placing concrete cover)	Forman & Labor 5	Operation	VA

Table 2: Probability distribution of the process

Process	Unit Flow	Distribution type	Distribution (min.)
Hauling rebars of T16 to the cutting Area	4	Triangular	a=3.25, m=4.33, b=6.83
Hauling Rebars T10 to the cutting area	10	Triangular	a=3.98, m=5.26, b=8.37
Cutting process for 4 Rebars T16 to 3 pieces one bar	4	Triangular	a=2.62, m=3.57, b=4.21
Cutting process for 4 Rebars T10 to 6 pieces one bar	4	Triangular	a=2.93, m=3.89, b=5.24
Cutting process for 6 Rebars T10 to 9 pieces one bar	6	Triangular	a=3.35, m=4.31, b=6.34
Hauling 24 pieces of T10 to the bending table (shape code 1)	24	Normal	m=1.6, SD.=0.5
Hauling 48 pieces of T10 to the bending table (shape code 2)	48	Normal	m=1.8, SD.=0.5
Bending process for 24 pieces of T10 (shape code 1)	1	Uniform	a=0.93, b=1.89
Bending process for 48 pieces of T10 (shape code 2)	1	Uniform	a=0.88, b=1.47
Hauling 12 pieces of T16 to the working Zone	12	Triangular	a=3.1, m=3.5, b=5.2
Hauling 24 pieces of T10 (shape code 1) to the working Zone	24	Triangular	a=1.88, m=2.55, b=3.65
Hauling 48 pieces of T10 (shape code 2) to the working Zone	48	Triangular	a=2.5, m=4.0, b=5.67
Rework	For 1 column	Triangular	a=9.5, m=8.0, b=11.0
Placing rebar according to the shop drawing	For 1 column	Triangular	a=10.2, m=12.86, b=14.96
Tightening the stirrups with the main bars	For 1 column	Triangular	a=11.3, m=13.6, b=18.25
Fix concrete cover	For 1 column	Triangular	a=1.96 m=2.5, b=5.23

3.2.2 Real-world model development

To evaluate the applicability of lean construction principles in the investigated construction process (reinforcement work), a corresponding simulation model is created for observed behavior. The main advantage of simulation methods is that they allow decision-makers to test the response of the system to different configurations. The base model is referred to as the "real world" model as shown in Figure (10 A,B), to ensure the results from the model the following is done:

- Model Testing: To define the required number of repetitions.

The following formula is used [32]:

$$N(m) = \left(\frac{S(m)tm{-}1, \frac{(1-\alpha)}{2}}{\bar{x}\ (m)\varepsilon} \right)^2$$

Given an initial set of m simulation runs, where N(m) represents the number of replications required, X(m) denotes the estimated mean μ from the m runs, and s(m) signifies the estimated standard deviation s from the m runs. The level of significance α, chosen as 95% in our study, and the allowable percentage of error ε for the estimated X(m), set at 5% in this paper, are also considered. The critical value of the two-tailed t-distribution at the significance level, denoted as tm–1,(1–α)/2, is essential. Initially, ten simulation runs were conducted, resulting in mean and standard deviation values of 177.42 minutes and 12.03 minutes, respectively (refer to Table 3). Based on a confidence level of 95% and an allowable error percentage of 5%, the value of t9,0.025 is determined to be 2.262. By applying the aforementioned equation, it can be deduced that the minimum number of replications necessary to yield reliable results exceeds 9.

- Model Validation: to confirm that there are no logical flaws and that the simulation model functions as intended. Validation is necessary because it shows that the produced model behaves similarly to the system that is currently in place [32]. The generated model was tested and confirmed using data from the actual world. The number of simulation runs required to achieve the required degree of accuracy must first be ascertained in order to do validation [33]. Generally speaking, more than one run of the model is needed to get satisfactory results. Yeh and Schmeiser recommend employing ten to thirty replications in order to attain the appropriate degree of accuracy [34, 35]. Consequently, ten simulation runs and the average of ten field observations from real-world scenarios were compared; the validation's final results are displayed in Table (4). As shown, there is an acceptable margin of error of less than five percent between the average of ten field observations from real-world scenarios and the ten replications for each model. So, the reinforcement process simulation model is now prepared for the implementation of lean concepts.

Table 3: Calculation of $\bar{x}$ (*m*) and *S*(*m*) for initial ten runs

Replications	Simulation cycle time (minutes)
1	163.4
2	174.82
3	165.96
4	167.11
5	165.63
6	178.36
7	175.30
8	206.70
9	167.73
10	209.20
$\bar{x}\ (m)$	177.42
$S(m)$	12.03

Table 4: Results of validation based on ten runs of models

Replications	Actual cycle time (min.)	Simulation cycle time (min.)
1	190	163.4
2	175	174.82
3	190	165.96
4	170	167.11
5	175	165.63
6	170	178.36
7	175	175.30
8	210	206.70
9	175	167.73
10	215	209.20
$\bar{x}\ (m)$	184.5	177.42
Variation (%)	3.837	

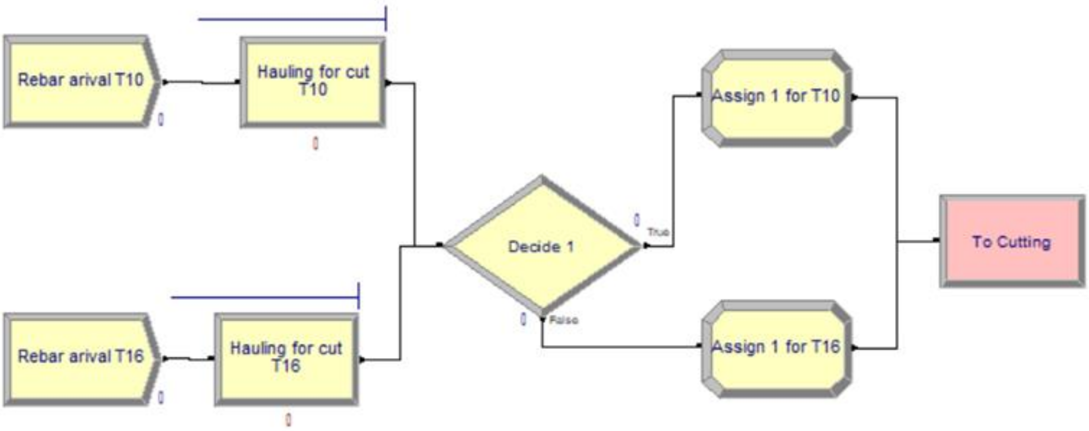

Figure (10 A): Real-world model simulation

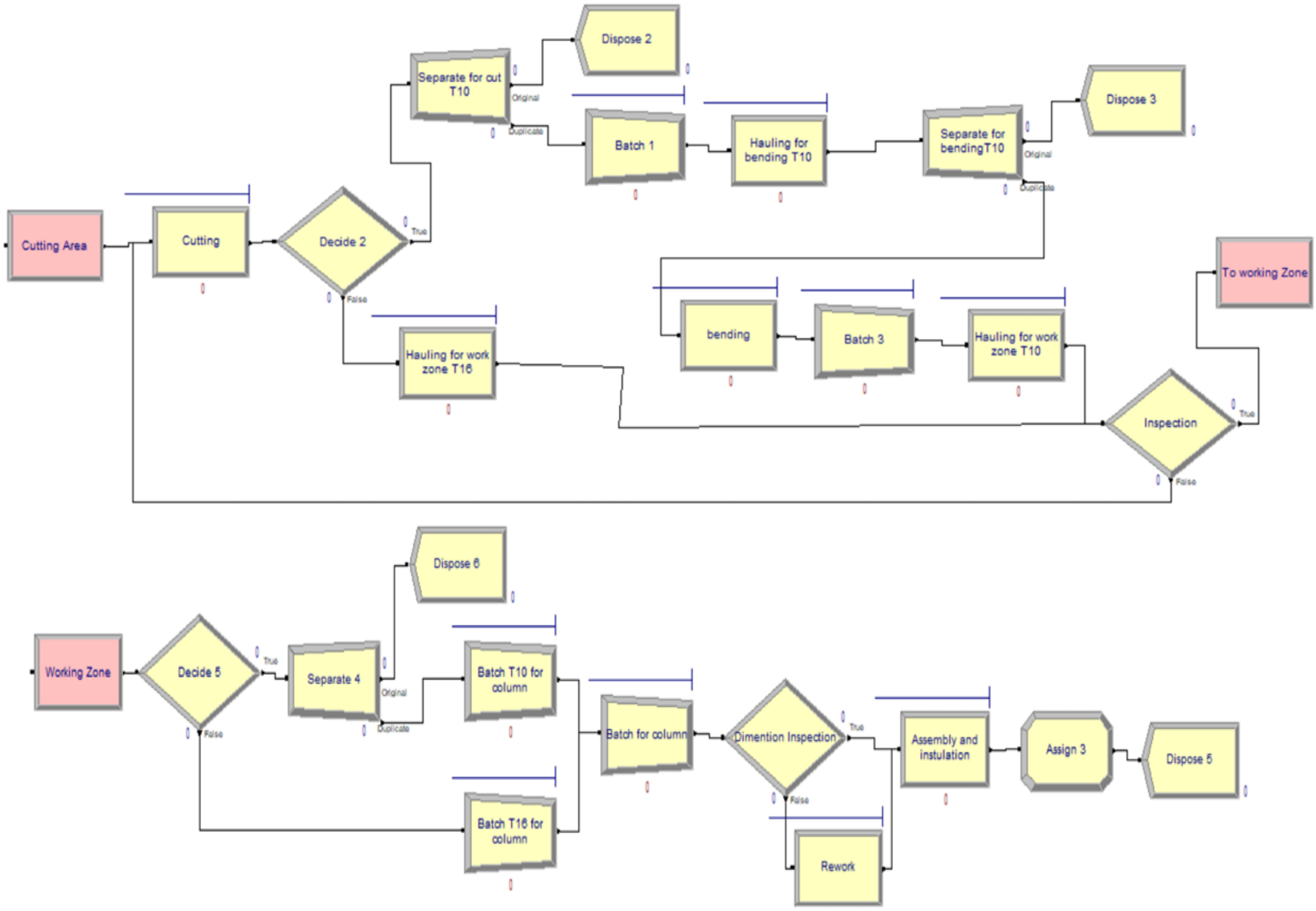

Figure (10 B): Real-world model simulation

3.2.3 Development of Lean Model

It's time to apply lean construction ideas to the current case study's reinforcing process after the real-world model has been designed, tested, and approved. Consequently, the process under observation is subjected to the three lean construction principles of generate flow, pull value, and seek perfection. Figure (11 A, B) shows the updated model (lean model), with all improvements included.

- Create Flow:

  - **Mistake-proofing concept (Poka-yoke concept):** The main goal of value creation is to reduce waste and avoid destruction [34]. According to the data collected, 5% of assembled column reinforcement are repaired or scrapped as material waste, meaning that defective steel bars go through the entire process before they even arrive at the assembly workstation, especially at the cutting workstation. The most common error that results in defective bars and stirrups is a poor cut of the rebar (wrong size or dimensions). This type of service requires additional cost and time not only in terms of rework but also in handling (bending, transport, etc.) the defective parts. Lean construction theory aims to prevent failures rather than wait for failures to occur [13]. For operators to solve problems quickly, defects must be detected early before they can be processed further; this concept is often referred to as lean production as error protection and is shown in Figure 11B as the inspection after each process.

- **Multi-skilled laborers:** Every worker carries out a certain duty, such as moving, chopping, bending, installing, and so on. For example, labor 1 and labor 2 are not available for use in more vital tasks since they are assigned exclusively to transport operations. The lack of a diverse workforce with different technical skills makes the process inflexible and reduces productivity[36, 37]. It appears beneficial to incorporate multi-skilled teams a typical component of lean processes into actual simulation models in order to evaluate prospective improvements in waste reduction (waiting time, inventory, etc.) and cost reduction in order to enhance the existing state of labor productivity. In order to guarantee an extra resource, new resource allocations have been put into place, taking into account the labor utilization rate and tool availability. Employees no longer need to travel great distances between workplaces, and—above all—value-creating workflows are expedited as a result of these workspaces now having access to additional resources that enable them to accomplish more balanced and efficient processes, as indicated in Table (5).

- Pull value "Reduce batch size". It was observed that steel bars were collected in large batches and then transported together to another workspace. This means workers spend a lot of time cutting the steel bars and then transporting them (e.g. bending area). Therefore, more material than necessary is provided, which also increases waiting time. This method negatively affects overall performance.

- Pursue perfection "Increased transparency." The process of transparency can be described as the extent to which a construction process (or its sub-processes) can communicate effectively. This technique has many advantages: (1) It has a positive effect on motivation; (2) Increases employee participation in continuous improvement initiatives through rapid action, understanding, and intervention to solve the problem; (3) Information improves the efficiency of planning and control; (4) Reduces sensitivity mistakes, especially in poorly organized workplaces.

3.2.4 Comparison of Real-world model and lean Model:

In order to assess how implementing lean construction principles affects waste reduction, the above construction process waste was calculated for both the real model and the lean model, and the results are summarized in Table (6). As shown, two types are identified in both the real-world and lean models for waiting in the process, this results in the overall process due to using skilled labor and rescheduling the labor tasks as shown in Table (5). The adoption of lean construction principles results in the improvement of time waste in the cutting and bending process and brings substantial value by enhancing productivity, saving time and costs, improving project predictability, and ultimately contributing to customer satisfaction and competitiveness.

Table 5: Resources assigned to activities in the reinforcement operation

Resources	Real Model Resources	Lean Model Resources
Transport T10 to the cutting place	Labor 1	Labor 1
Transport T16 to the cutting place	Labor 2	Labor 2
Cut Process for T10&T16	Labor 3	Labor 3 & Labor 5(half time)
Bending Process for T10	Labor 4	Labor 4 & Labor 2 (half-time)
Hauling cutting T10 to bending area	Labor 1	Labor 1
Hauling T10 to working Zone	Labor1	Labor 1
Hauling T16 to working Zone	Labor 2	Labor 2
Rework of defective bars	Forman, Labor 3, Labor 4	---
Dimension Inspection	Forman	-----
Cutting Inspection	---	Forman
Rework of cutting inspection defect	---	Forman, Labor 3
Bending Inspection	---	Forman
Rework of bending inspection defect	----	Forman, Labor 4
Installation of column (main Rft. , Stirrups, tightening and fix concrete cover)	Forman, Labor 5	Forman, Labor 5

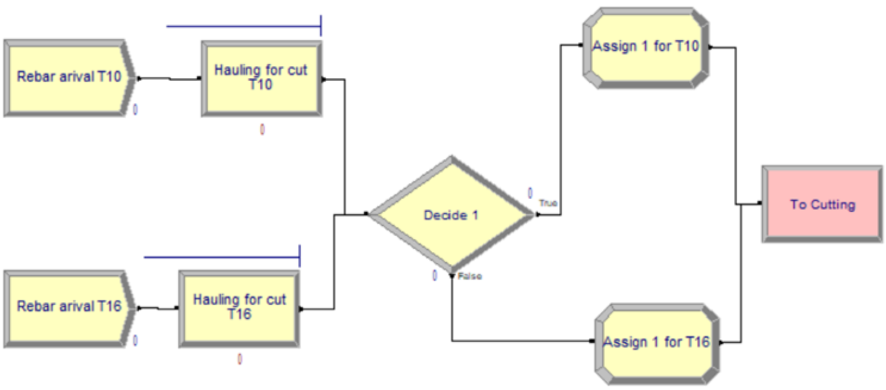

Figure (11 A): Lean model simulation

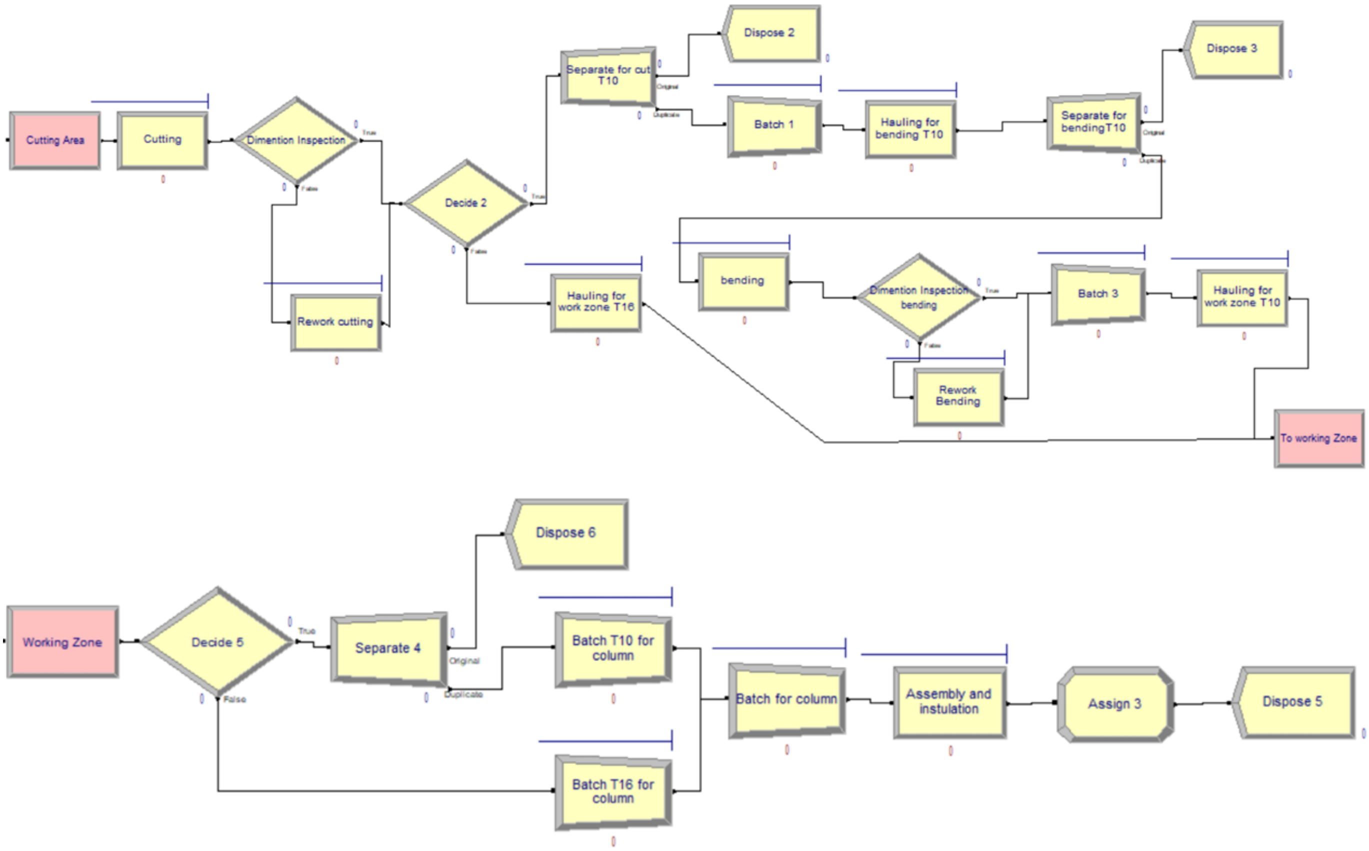

Figure (11 B): Lean model simulation

Table 6: Comparison of waste in the process

Process	Real World Model	Lean Model	Improvement %
Cutting	38.84	12.77	67.12 %
Bending	3.796	3.00	20.97 %

As a result of the previously mentioned improvement in the waste of waiting in the cutting and bending processes, a significant improvement was achieved by implementing lean principles in the process productivity Table (7).

The quantity of output generated in a given length of time is known as productivity. As shown below:

$$Productivity = \frac{Output}{Input}$$

In the real world, bricklaying processes yield labor productivity of 10.8 kg/man hours. With a 19.4% improvement, the lean simulation model raised this quantity to 13.5 kg/man-hours. An increase in outputs, or the installed quantity, justifies these outcomes. Every working day, the same resources (six labors) are taken into account. After using lean construction concepts, there has been a more equitable distribution of effort among staff. Having a multi-skilled work team meant that each worker could handle a variety of jobs instead of just one, allowing for greater resource use and increased labor productivity. This is consistent with other studies' findings, which showed that the primary factor resulting in better labor is the efficient utilization of workers' time.

The cycle time of the reinforcement process has improved by 24.40% after taking into account all of the aforementioned changes and rearranging the labor in the activities for the overall process of reinforcement. Table (8) illustrates this, with 10 replications of both the lean and real-world models. This outcome makes sense because the pulling concept (different priorities assigned to different activities) and flow view (batch size reduction) were applied in the reinforcement process, which resulted in a significant accumulation of unnecessary inventories in the working area where the final activities (placing and tightening the rebars and placing the spacers) are completed.

Table 7: Comparison of productivity improvement due to lean thinking implementation

	Daily production	Labor productivity (column/man-hour)	Labor productivity (kg/man-hour)	Total Improvement %
Real Model	2.7	0.064	10.816	19.6%
Lean Model	3.4	0.08	13.455	

Note: Quantities are the average of ten repetitions of the real model and the lean model.

Table 8: Comparison cycle time improvement due to lean thinking implementation

Cycle Time	Real World Model	Lean Model	Improvement %
	177.42	142.62	24.40%

Note: Quantities are the average of ten repetitions of the real model and the lean model.

4. Conclusion:

Better project outcomes, higher customer satisfaction, and enhanced long-term corporate performance can result from the effective application of lean construction. For this reason, in today's demanding and dynamic construction industry, construction organizations need to embrace lean principles and actively strive to remove waste from all processes in order to stay profitable and competitive.

The adoption of lean principles has proven to be effective in reducing waste across various industries. One of the key findings in the case study is that lean principles enhance the overall efficiency of processes by eliminating non-value-added activities, standardizing work procedures, and fostering continuous improvement. These practices lead to a reduction in wasted resources, reduction in wasted resources, such as the reinforcement process (improvement in cutting by 67.1% and in bending by 21%) and enhanced work productivity by 19.6%, and thus refinement in the overall time cycle by 24.5%.

Furthermore, lean principles promote the concept of just-in-time production, where materials and resources are acquired and utilized only when necessary. This approach helps to minimize inventory, reduce storage space requirements, and prevent overproduction, all of which contribute to waste reduction. Moreover, lean principles encourage employee involvement and empowerment, creating a culture of accountability and responsibility toward waste reduction. By engaging employees in waste identification, problem-solving, and process improvement, organizations can tap into their knowledge and experience, which often leads to innovative solutions and waste reduction. These benefits further support the notion that waste reduction through lean principles is a scientifically proven approach with tangible and measurable results. However, it is worth noting that the successful implementation of lean principles requires commitment from all levels of the organization, including top-level management, middle management, and frontline employees. Furthermore, ongoing training, communication, and monitoring are crucial for sustaining waste reduction efforts and continuously improving processes.

Finally, the scientific evidence overwhelmingly supports the use of lean principles for waste reduction. Organizations that embrace these principles stand to gain numerous benefits, including increased efficiency, reduced costs, enhanced quality, improved customer satisfaction, and minimized environmental impacts.

In summary, by adopting lean principles, businesses can create a more sustainable and efficient future while contributing to preserving natural resources and the environment by focusing on value-added processes. Further research could be conducted to explore the specific challenges and opportunities of implementing Lean Construction Principles in different developing countries. This would provide a clearer understanding of the contextual factors that influence the effectiveness of Lean principles in minimizing waste in construction projects.

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