Lean construction and simulation for performance improvement: a case study of reinforcement process

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Received 10 July 2019
Revised 10 May 2020
Accepted 6 July 2020

Abstract

Purpose – This research seeks to evaluate the impact of applying lean construction principles on the performance of reinforcement operations using a discrete-event simulation (DES) approach.

Design/methodology/approach – Process mapping of reinforcements operations was first established through field observation and interviews with construction managers involved in the selected project. Subsequently, quantitative data were gathered and then used to identify the best probabilistic density functions for each activity duration based on the fit-quality tests. Upon testing the validity of the real-world model, a lean simulation model was developed, using ARENA software, to investigate the impact of lean construction principles on the performance of such processes.

Findings – Lean principles are effective in enhancing the performance of the selected construction process. Output performance measurements for real-world model and lean model revealed that lean construction principles led to 41% improvement in process productivity, 14% enhancement in process efficiency and 17% reduction in cycle time.

Research limitations/implications – The statistical findings only represent the process under study (reinforcement process) and cannot be generalized to other construction activities. In order to draw generalizable conclusions, future works are needed to extend this study to different project sizes and more complex construction processes (e.g. bricklaying process and concrete pouring operations). Moreover, there are other factors such as labor skills, rework and uncertainty, site conditions that require further analyses for leaner construction projects.

Originality/value – The methodology and the techniques presented in this work can be used for decision making by analyzing various lean construction scenarios and evaluating their impacts on performance outcomes of any construction process prior to real-world implementation.

Keywords Construction process, Waste reduction, Performance, Lean construction, ARENA, Simulation

Paper type Case study

1. Introduction

Over the past two decades, the manufacturing industry has dramatically improved its output performance measurements such as efficiency, productivity and so on. There is no doubt that the concept "lean" has become the benchmark for industrial excellence in the manufacturing sector. Essential features of lean include a specific set of objectives, aimed at minimizing waste and producing the maximum value to the client. Bajjou *et al.* (2017) indicated that lean production has successfully decreased waste in manufacturing industry to 12%, while the construction industry is characterized with a higher waste rate with 57%. According to several studies, the construction industry is suffering enormously from a series of recurring problems such as cost and time overruns, low productivity, poor safety and quality and high rate of waste generation which decrease the value provided to the customer (Bajjou *et al.*, 2019; Bajjou and Chafi, 2018a, 2018b; Abbasian-Hosseini *et al.*, 2014; Harris and McCaffer, 2013). Construction characteristics (such as on-site production, complexity and uniqueness) also increase uncertainty and variability, which aggravates the above-mentioned problems (Bajjou *et al.*, 2017).

International Journal of Productivity and Performance Management
Vol. 70 No. 2, 2021
pp. 459-487

1741-0401
DOI 10.1108/IJPPM-06-2019-0309

Lean production is designed to ensure that the right product is manufactured with the right quality and quantity by supplying materials immediately when they are needed while keeping waste to a minimum and being flexible enough to adapt to changing production constraints (Bajjou and Chafi, 2020; Mao and Zhang, 2008). The lean production practices aim to optimize project performance through reducing waste and enhancing the value for the consumer (Mohammad and Oduoza, 2019; Bajjou and Chafi, 2018c; Dupin, 2014). The success of lean concepts has made this manufacturing philosophy a very promising opportunity for professionals and researchers in the construction field, as companies sought to survive and remain profitable under global competitive pressure. On the other hand, a literature review reveals that the majority of investigations are devoted to planning and control, while only a limited number of research studies are dedicated to testing the application of lean principles in the construction industry, especially in the construction phase.

In practice, it is obvious that it is very expensive and time-consuming to test a new construction technique. Therefore, to reveal an in-depth understanding of the potential impacts of lean thinking on the performance of construction projects, a simulation-based approach was adopted. Computer modelling and simulation are carried out before real-world implementation for two main reasons: (1) highlight and measure various types of construction process waste; (2) identify and test potential improvements to the system's performance with minimal risk, cost and time involved. Moreover, several researchers considered simulation modelling as a powerful approach that provides numerous benefits over mathematical and experimental modelling due to its marginal cost, flexibility, accuracy and realism (Abbasian-Hosseini *et al.*, 2014; Al-Sudairi, 2007; Hassan and Gruber, 2008; Nikakhtar *et al.*, 2015).

This paper aims to analyze and improve a reinforcement process by applying lean construction principles through computer simulation. The study starts with a literature review to provide a better understanding of lean production, lean construction principles and computer simulation modelling. Subsequently, the research methodology, results and discussions are then presented in detail. The conclusions and recommendations are finally elaborated.

2. Literature review

2.1 Lean production

The lean concept originated from Toyota production system, which focused on producing based on the customer needs (Dorval and Jobin, 2019; Garza-Reyes *et al.*, 2018; Bajjou and Chafi, 2018d, 2018e, 2018f; Harris and McCaffer, 2013). Subsequently, lean production became the universal term for describing the global application beyond the manufacturing industry. Lean production involves a combination of ideas such as waste elimination, teamwork, efficient use of resources, quality and safety improvement, continuous improvement and cooperative supply chain management (Agha *et al.*, 2010). According to Womack *et al.* (1990), lean production utilizes in general half of the total resources that are commonly required: materials, space, labors, equipment, etc. Lean production combines the advantages of both mass and craft production as it aims to enhance the performance of the entire production system by improving both machine and worker productivity (Gao and Low, 2014; Arleroth and Kristensson, 2011; Alinaitwe, 2009; Al-Sudairi *et al.*, 1999). Craft production is carried out by skilled workers in a decentralized organization (Awad, 2016). Mass production, first developed by Henry Ford and then developed by Alfred Sloan, involves specialized workers or machinery making the same standardized part of the product the whole time while the product moves on an assembly line (Gao and Low, 2014). Workers are not integrated into the continuous improvement process. Lean production involves variable product volumes manufactured by multi-skilled employees using flexible and automated machines (Al-Sudairi *et al.*, 1999).

With the widespread and growing popularity of lean, practitioners considered lean as a series of tools and practices, but it is now widely perceived as a very basic business approach. As Diekmann *et al.* (2004) stated, "lean cannot be reduced to a set of rules or tools. It must be approached as a system of thinking and behavior that is shared throughout the value stream."

2.2 Waste under lean production

Under lean production, activities included in each production cycle (from conception to final delivery) can be divided into three main categories: value-adding (VA) activities, non-value adding but required (NVAR) and non-value adding (NVA). VA activities are those that are involved in creating value by modifying the function, form or shape of materials or information to satisfy the customer's requirements (Diekmann *et al.*, 2004). On the other hand, VA activities are defined as the specific activities that the customer is considering purchasing (Diekmann *et al.*, 2004). NVAR activities can be split into three different subcategories required for construction processes, but that do not have a lasting effect on the final product. These subcategories comprise process inspection, material positioning and temporary work and support activities (TWSA). NVA activities are those that consume resources, time or space but do not contribute to value creation for the product or service needed by the customer. This category includes eight types of waste (Narayanamurthy *et al.*, 2017; Bajjou *et al.*, 2017; Antony *et al.*, 2012; Wang *et al.*, 2009):

(1) Overproduction: overproduction involves more material/workers/equipment than is required to meet customer requirements, which results in a higher amount of production than is needed.

(2) Unnecessary transportation: Inefficient workflows include work-in-progress, finished products or parts moving over significant distances between work stations.

(3) Unnecessary motion: Any unnecessary movement that employees perform as part of their daily work, such as searching for, grabbing or stacking tools, parts, etc. Walking is also considered a motion waste.

(4) Excess inventory: The surplus at any stage of the workflow – whether it is work in progress, raw materials or end products – results in excessive expenses in terms of storage, transport and liability costs.

(5) Waiting: The most directly visible waiting effect is the inability to perform immediately a task due to a shortage of (labors, materials, information, equipment, validation, etc.) or due to downtime, delays, bottlenecks.

(6) Defects: Inspecting, producing, repairing, replacing or disposing of defective products or part is signification waste of time and cost and directly influence the performance of any project.

(7) Over-processing: Ineffective processing leads to deficiencies, while excessive processing leads to unneeded high quality; both are regarded as waste.

(8) Unused employee creativity: Under or even non-utilization of the potential of staff, loss of skills, ideas, opportunities for improvement represents a major source of waste for companies.

2.3 Lean construction

Koskela (2000) reported that the construction industry is mainly managed based on the transformation view, which implies that each process or sub-process is regarded as a conversion of inputs to outputs. The output value and the total processing cost are only impacted by the input value and cost, respectively. Thus, to improve the performance of construction processes the focus must be on the inputs of the process. However, managers largely ignore value generation and flow concepts. As a result, this view leads to a considerable amount of waste and loss of value in construction processes. On the other hand, lean construction gives high importance not only to transformation steps but also to flow steps (waiting, inspection, etc.). Studies have shown that flow activities in construction processes constitute 30–50% of the total project cost, which represents a real challenge for construction projects managers (Larsson, 2008). Lean construction theory is based on five main principles (Aziz and Hafez, 2013; Womack and Jones, 1996; Wu and Low, 2011): (1) specify value: identify the value of the activities based on the ultimate customer's view and determine their natures under lean construction concept, whether they are VA activities, NVAR and NVA; (2) map the value stream: Identify how value is created, when value is delivered and where improvements are to be taken. Process mapping is a key technique in value stream because it allows bringing a better understanding of the logic of the process and detecting where waste exists, hence, decisions can be made to improve the current process; (3) make value flow without interruptions: the main target is to achieve a continuous flow by reducing unnecessary movement, defects, scrap, queuing and workers waiting times; (4) pull value: adopt pull concept in the construction process instead of push, which means that the necessary materials, parts or information must be delivered to the next customer (downstream) as soon as needed; (5) pursue perfection: keep improving the process through eliminating the remaining waste factors and increasing the transparency of construction sites.

2.4 Computer simulation and lean construction

Lean construction aims to enhance the performance of the construction processes by eliminating waste and improving quality (Bajjou *et al.*, 2017). According to Van der Merwe (2017) and Wang *et al.* (2009), simulation modelling is the most effective way to test the impact of lean construction principles on construction processes prior to physical implementation. Halpin and Kueckmann (2002) considered simulation-based approach as a part of lean construction toolset. In addition, Robinson *et al.* (2012) confirmed the compatibility between DES application and the original seven waste recognized by lean production. Review of previous works also shows that computer simulation has emerged as a successful and powerful tool for modelling and analyzing the applicability of lean construction concepts in construction processes (Abbasian-Hosseini *et al.*, 2014; Agha *et al.*, 2010; Al-Sudairi, 2007; Bamana, 2018; Halpin and Kueckmann, 2002; Hosseini *et al.*, 2012; Mao and Zhang, 2008; Wang *et al.*, 2009). For instance, Halpin and Kueckmann (2002) demonstrated that the combination between lean construction and computer simulation provide very impressive operational gains in construction processes such as concrete forming and wall erection. Based on a simulation-based approach, Wang *et al.* (2009) applied flow production and lean construction principles to a pipe spool shop fabrication and, as a result, improved the production performance. Mao and Zhang (2008) developed a framework for construction processes reengineering that integrate computer simulation and lean principles techniques. Abbasian-Hosseini *et al.* (2014) evaluated lean construction benefits using simulation technique for a bricklaying process and the results were very significant; 27% increase in operational efficiency; 41% decrease in cycle time, 43% increase in productivity. Bamana (2018) tested how just-in-time, being a key tool of lean construction, can be applied in wood construction through simulation. The best scenario allowed 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

(AbouRizk, 2010). STROBOSCOPE (Hassan and Gruber, 2008), CYCLONE (Alkoc and Erbatur, 1998), Extend™ (Larsson, 2018.), Extend + BPR® (Al-Sudairi, 2007), SIMPHONY (Wang *et al.*, 2009), WITNESS (Nikakhtar, 2011) and SIMIO (Bamana, 2018) are some simulation software implemented more widely used by construction researchers. ARENA is DES software based on SIMAN language with a powerful and advanced 3D graphical interface (Herron and Hicks, 2008). In general, ARENA helps in modelling 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 company partnering with the research team selected the simulation for the following reasons:

(1) Computer simulation is a powerful solution because it ensures an appropriate environment in which decision-makers can more effectively design, analyze and improve processes through experimentation in a controllable and low-cost system (Wang and Halpin, 2004).

(2) The simulation approach is compatible with lean concept. As stated by Halpin and Kueckmann (2002): "lean thinking and simulation are very closely linked and even synonymous."

(3) Simulation generates accurate quantitative outputs such as cycle time, daily throughput, productivity, crew utilization. In addition, it allows measuring various types of waste (waiting, transport, rework...).

(4) The integration of Lean and DES provides convincing arguments to support the adoption of Lean. With DES, process behaviors can be assessed prior to physical implementation and redesigned until the targeted performance has been met.

3. Research methodology

Construction projects involve critical decision-making mechanisms (Nikakhtar *et al.*, 2012). However, construction managers often make decisions intuitively or based on their experiences. It is obvious that these techniques do not lead to the most efficient construction process. Furthermore, readjusting the construction process once starting the physical test is very expensive and time time-consuming. Therefore, designing and improving the construction process, especially using new methods such as lean construction, can be challenging. Computer simulation is a powerful solution as it provides an appropriate environment in which decision-makers have the ability to design, analyze and improve processes more effectively through experimentation with a controllable and low-cost system. Simulation is also provides a better understanding of the workflow in any construction process. Therefore, in order to reveal a thorough understanding of the potential impacts of lean on the performance of construction projects, a simulation-based approach was adopted. Computer modeling and simulation are performed prior to implementation in the real world for two main reasons: (1) to highlight and measure various types of construction process waste, (2) to identify and test potential improvements to system performance with minimal risk, cost and time involved. In addition, many researchers consider simulation modeling to be a powerful approach that offers many advantages over mathematical and experimental modeling because of its marginal cost, flexibility, accuracy and realism. There are numerous simulation based-approaches such as system dynamics, agent-based and discrete event simulation (DES). The current study opted for DES to achieve its objectives because it is compatible with the major construction wastes which allow measuring the impact of introducing lean construction concepts.

Figure 1 illustrates the research flowchart of our case study. A real experiment is required to examine and assess the effectiveness of lean construction principles on waste reduction in

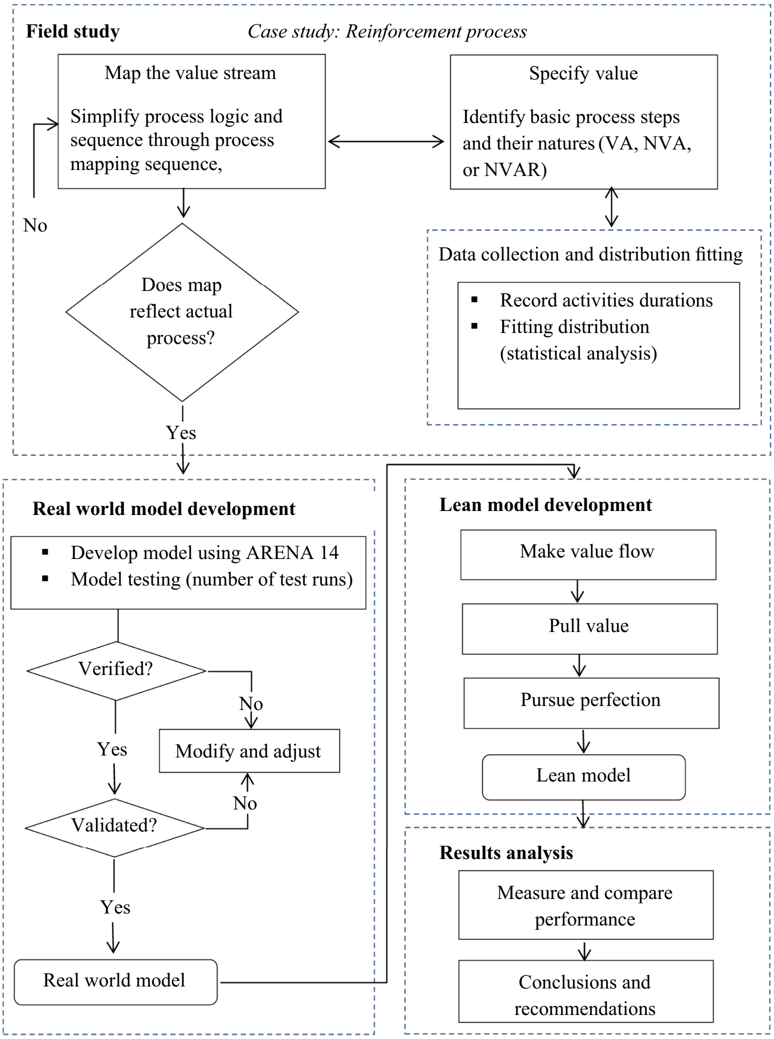


Figure 1.
Research flowchart

construction processes. Hence, the current study focused on a case study of a reinforcement process of a five-floor building to provide an empirical basis for a valid model. The reinforcement process is repeated every working day which includes several activities and resources that are interconnected with each other. These operations are daily, time-consuming and arduous. The cyclical nature of this process ensures its relevance to the evaluation of lean by computer simulation.

The current work represents the results of an original structured approach based on a combination of five lean construction principles (identify the real value, map the value stream, flow, pull and perfection) and conventional simulation modelling steps (data collection and fitting of activities duration, model testing/validation/verification, model improvement, analyzing and comparing results between real-world model and the improved model). The methodology proposed in this work starts with a field study based on two lean construction principles: 1 – specify value, 2 – map the value stream. These principles aim to understand the structure and logic of reinforcement activities and design the current state of the value stream (nature of tasks, process flow, sequences of operations) which helps identify the actual problems and therefore make decisions regarding potentials improvements to the overall system's performance. The data were obtained by accurately monitoring the reinforcement process of the foundation. Different continuous-distribution functions were then evaluated using the data gathered and the most reliable ones were selected based on the fit-quality tests.

After checking that the developed map reflects the actual process and finding the best fitting distribution of reinforcement activities, an initial simulation model was developed using ARENA simulation software. Subsequently, validation and verification steps were performed to adjust the model in such a way that it will be more consistent with the actual functioning of the process under study. The initial model was run through several iterations to establish a verified and valid model (real-world simulation model). Afterward, three lean construction principles (flow, pull and perfection) were tested, which led to an improved model (lean simulation model). Output performance measurements were compared between both real-world and lean model to test the effectiveness of lean construction principles in improving construction process performance.

4. Case study: reinforcement process

The case study is based on a medium-sized concrete construction project in Casablanca, Morocco. This work focused on a construction project "ENNASSR 1" consisted of 21 five-floor buildings occupying a surface area of 7,150 m^2. Figure 2 shows a 2D graphical view of the selected project.

Due to the large amount of waste in reinforcement operations in the project under study, engineering managers decided to test the potential effects of applying lean construction principles in this process. Operations of the reinforcement process are carried out by a subcontractor on the construction site. Five labors and one foreman dealt with the task of the reinforcement process. The steels are supplied in the form of long bars with high adhesion. The reinforcement process of the studied project contains the following workstations: (1) inventory of steel: contains two types of long bars (12 m) which are: transverse rebars (TR) with a diameter of 6 mm and longitudinal rebars (LR) with a diameter of 12 mm; (2) cutting area: The cutting of the steel bars, which have been moved from the storage area to the cutting area, is done with a bolt-cutter; (3) bending area: TR are shaped on a bending table; (4) assembling area: bent rebars (pieces of TR) and cut rebars (pieces of LR) are assembled

Figure 2.
2D graphical view of the project under study

manually using annealed steel binding wire; (5) foundation area: after controlling assembled reinforcements dimensions (bean cages) are finally placed at the foundation level. A simple representation of reinforcement process is illustrated in Figure A1.

4.1 Field study

4.1.1 Identify value. To simplify the studied process and define the value generated at the operational level, the reinforcement process was split into a series of activities. Each component of the workflow was recognized as a VA or NVA activity based on field observations and off-site and on-site interviews with project managers, foremen and engineers. These interviewees were selected because of their awareness of the ultimate and interim customer needs as well as their expertise in the process under study. Using lean production as the foundation, the nature of activities were categorized into VA, NVAR and NVA. For example, "assembling process," is a VA operation because it affects the form, shape or function of materials (Diekmann *et al.*, 2004). However, "placing assembled rebars beam cage" is considered as an NVAR as it has no actual effect on the physical characteristics of materials. Hence, it was subcategorized as a material positioning which is a NVAR but, on the other hand, activities such as transportation and rework are classified as NVA because they do not increase value to the customer. Table 1 shows the basic process steps and their natures as well as resources assignment.

4.1.2 Map the value stream. After the identification of the main steps of the reinforcement process as well as their nature, classification and resources, it seemed necessary to establish the interactions between the different activities for a better understanding of the studied case. According to (Abbasian-Hosseini *et al.*, 2014; Al-Sudairi, 2007; Nikakhtar, 2011; Nikakhtar *et al.*, 2015), linkages between activities and the material flow in any construction process can be schematized by process mapping technique. Process mapping aims to simplify process logic and sequence and hence search for potential improvements. A preliminary process maps were first developed based on field observations and then revised, adjusted and validated through discussions with process supervisors. In order to make the discussions more fruitful, several questions were used which are (Al-Sudairi, 2007):

(1) What must be completed before this activity can be starts?

(2) Can this activity take place simultaneously with any other activity?

(3) What are the expected outcomes of each activity?

Figure 3 shows the general process map of the studied reinforcement process using the symbols of operations process chart (OPC). OPC symbols are clarified in Table A1. Moreover,

Table 1.
Basic process steps classification

Process steps	Labors	Nature of activity	Classification
Hauling TR to cutting area	Labor 1	Transportation	NVA
Hauling LR to cutting area	Labor 2	Transportation	NVA
Cutting process TR	Labor 3	Operation	VA
Cutting process LR		Operation	VA
Hauling cut rebars TR	Labor 1	Transportation	NVA
Bending process TR	Labor 4	Operation	VA
Hauling matched pieces	Labor 2	Transportation	NVA
Assembly process	Labor 5	Operation	VA
Hauling assembled rebars beam cage	Labor 2	Transportation	NVA
Rework of defected cages	Foreman	Rework	NVA
Placing assembled rebars beam cage	Foreman	Material positioning	NVAR

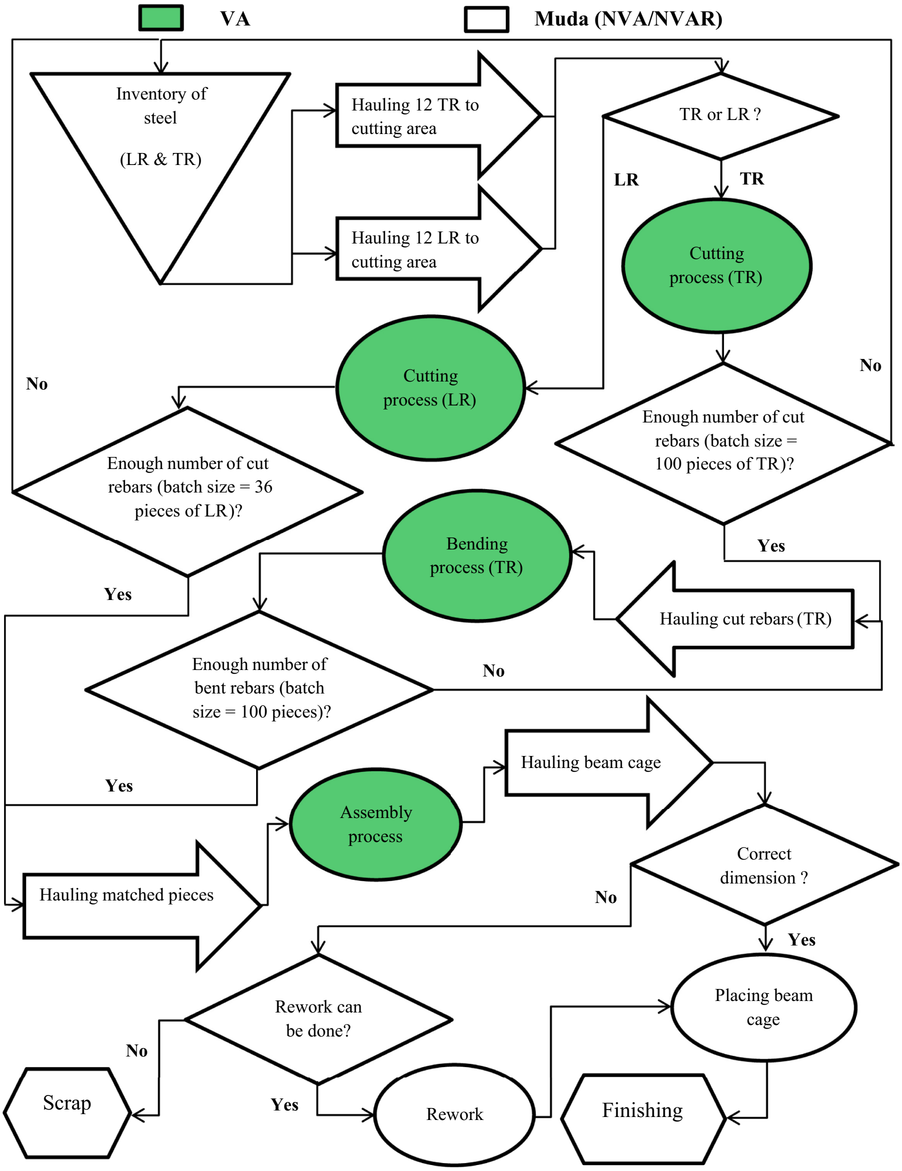


Figure 3.
Process map of the reinforcement process

all activities are classified into two categories according to their natures: VA and NVA activities (Muda I and Muda II). More process details are reflected in the stage of model development.

4.2 Data collection and distribution fitting

After the logic of the process map was designed, it is time to collect and statically analyze quantitative data related to each work task. The collected empirical data are in general limited and do not allow adequate analysis flexibility (Hassan and Gruber, 2008). Hence, each source of randomness in the system must be modeled with an appropriate probability distribution density function to provide an accurate simulation of the system's response. For data collection, a video camera was installed to film all the tasks included in the studied reinforcement process. The video recording was performed in a non-impacting manner on worker performance. Subsequently, durations for each task were measured using a chronometer. 30 data points were collected for each step in the process to ensure the reliability of the input data for the simulation model. For fitting distributions, this number of observations is considered enough for statistical analysis (Abbasian-Hosseini *et al.*, 2014; Hassan and Gruber, 2008).

Many software packages have been deployed for probability distribution fitting to a sample data. Using such packages make the stage of probability distributions fitting to a sample data accurate, easy and quick (Abbasian-Hosseini *et al.*, 2014). Using EasyFit, which is commercial software, 24 continuous distributions (such as Weibull, Johnson SB, Triangular and Normal) were experienced for the dataset and the most appropriate ones were selected based on the goodness-of-fit tests (Kolmogorov–Smirnov tests, chi-squared, Anderson Darling). In the following section, an illustrative example of the activity duration of "assembly process" is presented. The dataset for this activity was fitted to Triangular density distribution:

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

where m is the most likely value and a, b are continuous boundary parameters ($a < b$).

Figure 4 illustrates a comparison between the collected data of the assembly process and the triangular distribution. This probability distribution was validated using the goodness-of-fit tests (Kolmogorov–Smirnov tests, chi-squared, Anderson Darling) since none of the mentioned tests reject null hypotheses (H_0: the date follow the specified distribution) at a significance level of 0.05.

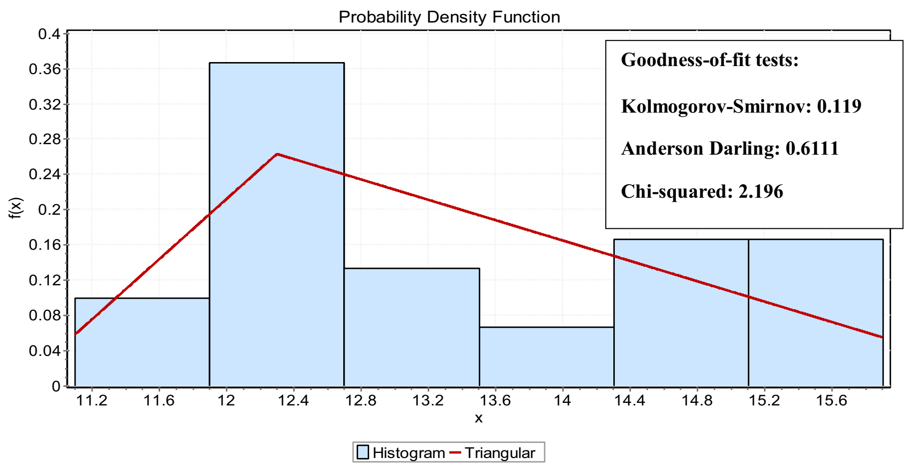


Figure 4.
Comparison between the collected data and the fitted distribution of the activity "assembly process"

Similarly, the best promising probability distributions for each activity as well as their parameters were determined following the same technique, as shown in Table 2.

5. Real world model development

As mentioned in the previous sections, the primary strength of using a simulation approach is to enable decision-makers to test the system's response to different set-ups. Before starting evaluating the applicability of lean construction principles in the studied construction process (reinforcement operations), a simulation model should be established according to the observed behavior. Hence, waste classifications for each activity, process map as well as the best-fitted distributions for each activity were employed as input to develop the simulated model using ARENA 14. In this study, the basic model is referred to "real-world" model, as shown in Figure 5.

It is worth mentioning that the final product of the chosen process (beam cage) is the result of a series of operations such as (cutting, bending and assembly) that were performed on either an individual part or a batch of elements flowing through the simulation model. In other words, each cage does not flow through the system network as a single entity. Rather, it circulates in the form of raw materials (TR or LR) or a few pieces (cut rebars, bent rebars). To accurately develop the real-world simulation model, different modules (Batch, Decide, Separate, Process, Assign, etc.) were deployed to transmit the actual behavior to the developed model. The function of each module is explained in Table A2. The key to successful modelling is the development of a basic model that clearly describes the current workflow sequence and the interactions between the various work tasks.

5.1 Model testing

Prior to experience the impact of lean principles, it is important to test the simulated model. Typically, a single run of the developed model is not enough to generate relevant results

Process steps	Unit of flow	Probability density functions (PDF)	Distribution parameters (minutes)
Hauling 12 TR to cutting area	12 TR	Johnson SB	$\gamma = 0.37$ $\delta = 0.92$ $\lambda = 3.14$ $\zeta = 0.92$
Hauling 6 LR to cutting area	6 LR	Johnson SB	$\gamma = 0.59$ $\delta = 0.81$ $\lambda = 2.26$ $\zeta = 1.13$
Cutting process TR	2 TR	Weibull	$\alpha = 5.77$ $\beta = 4.3514$
Cutting process LR	1 LR	Gamma	$\alpha = 22.30$ $\beta = 0.15$
Hauling cut rebars TR	20 pieces of cut rebars (TR)	Johnson SB	$\gamma = -0.60$ $\delta = 0.76$ $\lambda = 0.80$ $\zeta = 1.16$
Bending process TR	5 pieces of cut rebars (TR)	Uniform	$a = 0.88$ $b = 1.47$
Hauling matched pieces	20 pieces of bent rebars (TR) & 6 pieces of cut rebars (LR)	Weibull	$\alpha = 5.46$ $\beta = 2.18$
Assembly process	20 pieces of bent rebars (TR) & 6 pieces of cut rebars (LR)	Triangular	$a = 10.76$ $m = 12.30$ $b = 16.85$
Hauling assembled rebars beam cage	1 cage	Uniform	$a = 0.53$ $b = 1.97$
Rework of defected cages	1 cage	Normal	$\mu = 7.61$ $\sigma = 1.09$
Placing assembled rebars beam cage	1 cage	Johnson SB	$\gamma = 0.37$ $\delta = 0.66$ $\lambda = 2.31$ $\zeta = 3.00$

Table 2. Probability distribution of reinforcement process revealed by easy fit

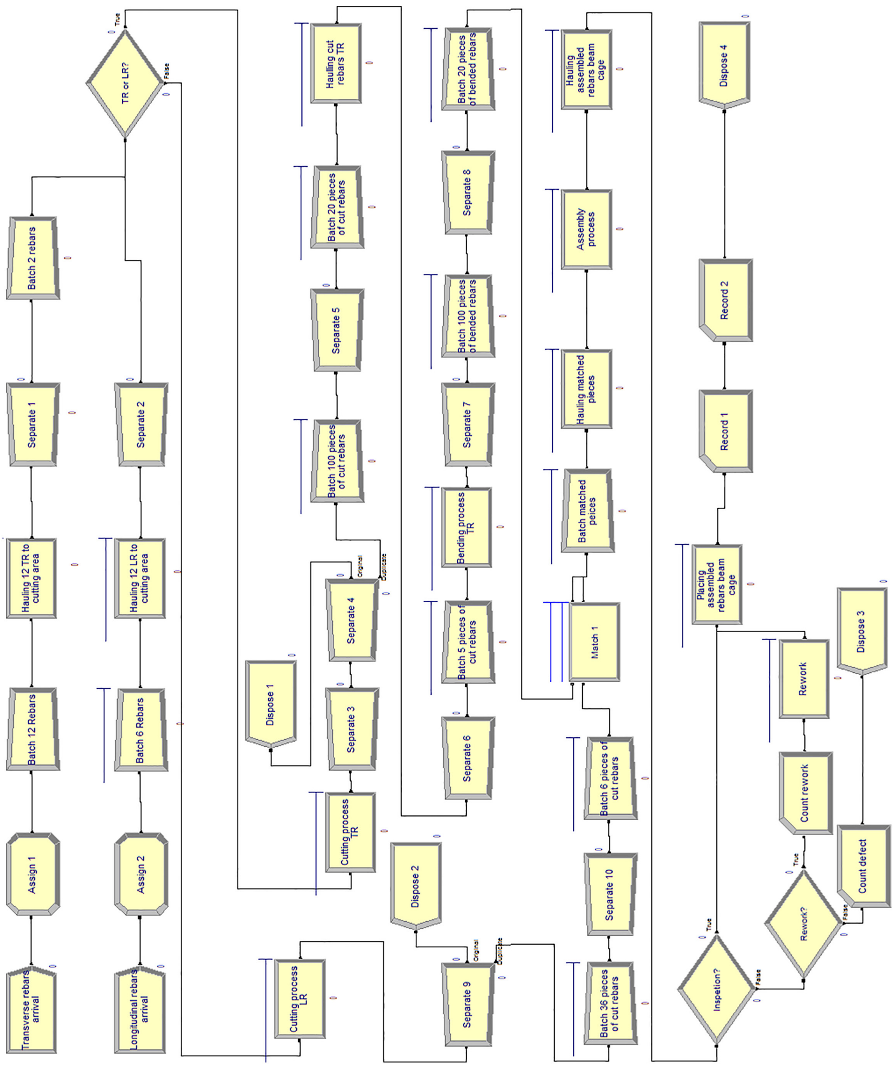


Figure 5.
Real-world simulation model of reinforcement process by arena

(Hassan and Gruber, 2008; Kamrani *et al.*, 2014). To define the required number of replications the following formula (Abbasian-Hosseini *et al.*, 2014; Nikakhtar *et al.*, 2012; Toledo *et al.*, 2007) was employed:

$$N(m) = \left(\frac{S(m) t_{m-1, \frac{(1-\alpha)}{2}}}{\overline{X}(m) \varepsilon} \right)^2 \quad (1)$$

where: $N(m)$ is the number of replicates required to obtain the intended level of accuracy, given m initial runs; $\overline{X}(m)$ m is the mean μ obtained from m replications; $S(m)$ is the standard deviation obtained from m replications; a is the significance level considered (α = 95% in this study); ε is the acceptable error percentage considered for the estimated $\overline{X}(m)$ (ε=5% in this study); and $t_{m-1, \frac{(1-\alpha)}{2}}$ is the critical value of the two-tailed t-distribution at the considered level of significance.

It is worth mentioning that the data collected for the estimation of the mean and standard deviation are the construction process cycle time resulting from running the model. $\overline{X}(m)$ and $S(m)$ are calculated based on six initial runs (m = 6), as shown in Table 3; $t_{5,\ 0.025}$ is equal to 2.571 at a confidence level of 95% and an acceptable error percentage of 5%.

Using Eqn (1), the appropriate number of model runs to produce sufficient results for model validation and reach the desired level of accuracy must be greater than 4.

5.2 Model verification

Model verification is an essential step in ensuring that the simulation model is operating as intended and has no logical errors. Basically, the verification stage is expected to evaluate the suitability of the systematic presentation of the model through computer examination and code testing and measurement of uniformity based on the model's statistical approach. More specifically, Verification involves four points: (1) examining the model logic, (2) running simulation tests, (3) monitoring the trajectory of entities in the model network and (4) consistency assessment (Herron and Hicks, 2008). On the other hand, according to Back (1994), the verification mainly considers two questions, which are as follows:

(1) Does each transaction follow the logical path in the model network under all conditions?

(2) Does each transaction perform what it is supposed to be performed under all conditions?

For example, the verification of the activity "assembly process" is performed through comparing the total throughput of labor in the real world and in the simulation model. The

		Construction process cycle time
Replication	1	310.49
	2	308.03
	3	293.69
	4	323.99
	5	292.99
	6	318.31
$\overline{X}(m)$		307.92
$S(m)$		12.63

Table 3. Calculation of $\overline{X}(m)$ and $S(m)$ for six initial runs

results of ten run tests of the model show that labor 5 was occupied in 65.55% of the total time of the process (480 min). This implies that the time spent by labor 5 in the activity "assembly process" is 314.64 min (0.6214 * 480). Besides, according to the collected data for "assembly process," the average time to complete assembling one beam cage is 13.37 min. Thus, labor 5 assembled cages 22.04 times (314.64/13.37) and it is almost equal to the total number seized (23.00 times), as shown in Figure 6, which indicates that the selected activity could be considered as verified. Following the same way, all activities were accurately exanimated and verified following similar steps.

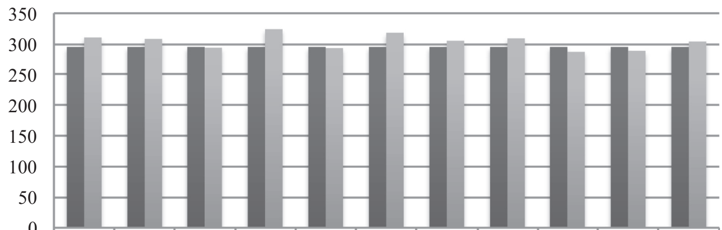
5.3 Model validation

Once the verification steps are completed, it is time to perform model validation activities to develop a realistic model. Validation signifies that the developed model is behaving in a similar way to the existing system (Farrar *et al.*, 2004). To do so, the outputs of the simulated model should be compared to the collected data gathered from the process under study (Banks et *al,* 2005). One of the relevant criteria for illustrating the similarity between real and simulated model is the cycle time (Abbasian-Hosseini *et al.*, 2014). Cycle time is the total time spent in moving a unit through a physical process from the start to the end (Maunzagona, 2017). Time is a powerful measure compared to quality and cost as it has an influence on both (Krupka, 1992). The average of 10 simulation runs was compared to the actual cycle time. In addition to the comparison based on cycle time, the average daily production (8 working hours) was also compared to the outputs of 10 test run of the simulation model. Two criteria were adopted to ensure the reliability and validity of the developed model. The results are illustrated in Figures 7 and 8. As can be notified, the difference between the collected data and the outputs of 10 test runs regarding cycle time and daily production are 2.94% and 4.76%, respectively. The difference is less than 5% for the selected factors (cycle time, daily production) which is acceptable (Abbasian-Hosseini *et al.*, 2014; Abbasian Hosseini *et al.*,

Labour 5

Usage	Value			
Scheduled Utilization	0.6214			
Number Scheduled	1.0000	(Insufficient)	1.0000	1.0000
Total Number Seized	23.0000			
Instantaneous Utilization	0.6214	(Insufficient)	0	1.0000
Number Busy	0.6214	(Insufficient)	0	1.0000

Figure 6.
Simulation outputs for labor 5 performance



	1	2	3	4	5	6	7	8	9	10	Means
■ Actual cycle time (min)	295	295	295	295	295	295	295	295	295	295	295
■ Simulated cycle time (min)	310	308	294	324	293	318	305	309	287	289	304

Figure 7.
Final results of validation based on ten replications of the real-world model (based on cycle time)

2012; Hassan and Gruber, 2008). The validity of the model developed is thus proven and it is now ready for further evaluation.

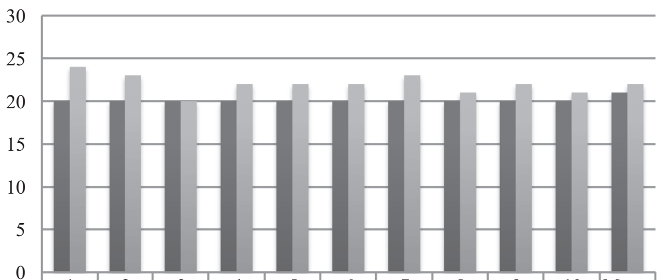
6. Lean model development

Once the real-world model has been developed verified and validated, hence, it is time to improve the reinforcement process by introducing lean construction principles. Accordingly, three lean construction principles are applied to the observed process, which are (1) make value flow; (2) pull value; and (3) pursue perfection. The improved model (lean model), including all improvements, is illustrated in Figure 9.

6.1 Make value flow

6.1.1 Mistake-proofing concept. The main objective behind making value flow is to reduce waste and avoid interruption (Abbasian-Hosseini *et al.*, 2014). Based on the collected data, 10% of assembled cages are repaired or scrapped as material waste, which means that defective reinforcing rebars are flowing through the whole process even before reaching the assembly workstation, especially in the cutting workstation. The most frequent error that results in a defective cage is the occurrence of poorly cut rebars (wrong dimension or size). This kind of performance results in additional costs and time not only at the level of reworking operations but also during the processing (bending, hauling, etc.) of defective parts. Lean construction theory aims to prevent errors rather than waiting for them to occur (Nikakhtar *et al.*, 2015). Defects must be detected as early as possible before further processing to allow the operator to quickly solve the problem; this concept is commonly known, under lean production as mistake-proofing. To improve the current situation, self-inspection will be applied in the cutting area which is the main zone susceptible to errors such as. Hence, if any defect is detected the rework operations should be started before sending rebars to the next workstations. Additionally, to reduce the rework rate two modules have been introduced into the real-world model "Color rebar TR" and "Color rebar LR." These modules are designed to identify, using colors, the exact position for the cutting operation before starting cutting process; hence, this will help reduce the risk of errors and simplify the work for labors and if any error occurs defective parts will pass through "rework" modules. This practice is in accordance with lean construction philosophy that is widely known as Poka-yoke concept.

6.1.2 Multi-skilled labors. As previously shown in Table 1, each labor performs a specific task such as hauling, cutting, bending and so on. For instance, labor 1 and labor 2 are assigned only to transport operations which prevent their use in more critical operations.



	1	2	3	4	5	6	7	8	9	10	Means
■ Actual daily production (cage)	20	20	20	20	20	20	20	20	20	20	21
■ Simulated daily production (cage)	24	23	20	22	22	22	23	21	22	21	22

Figure 8.
Final results of validation based on ten replications of the real-world model (based on daily production)

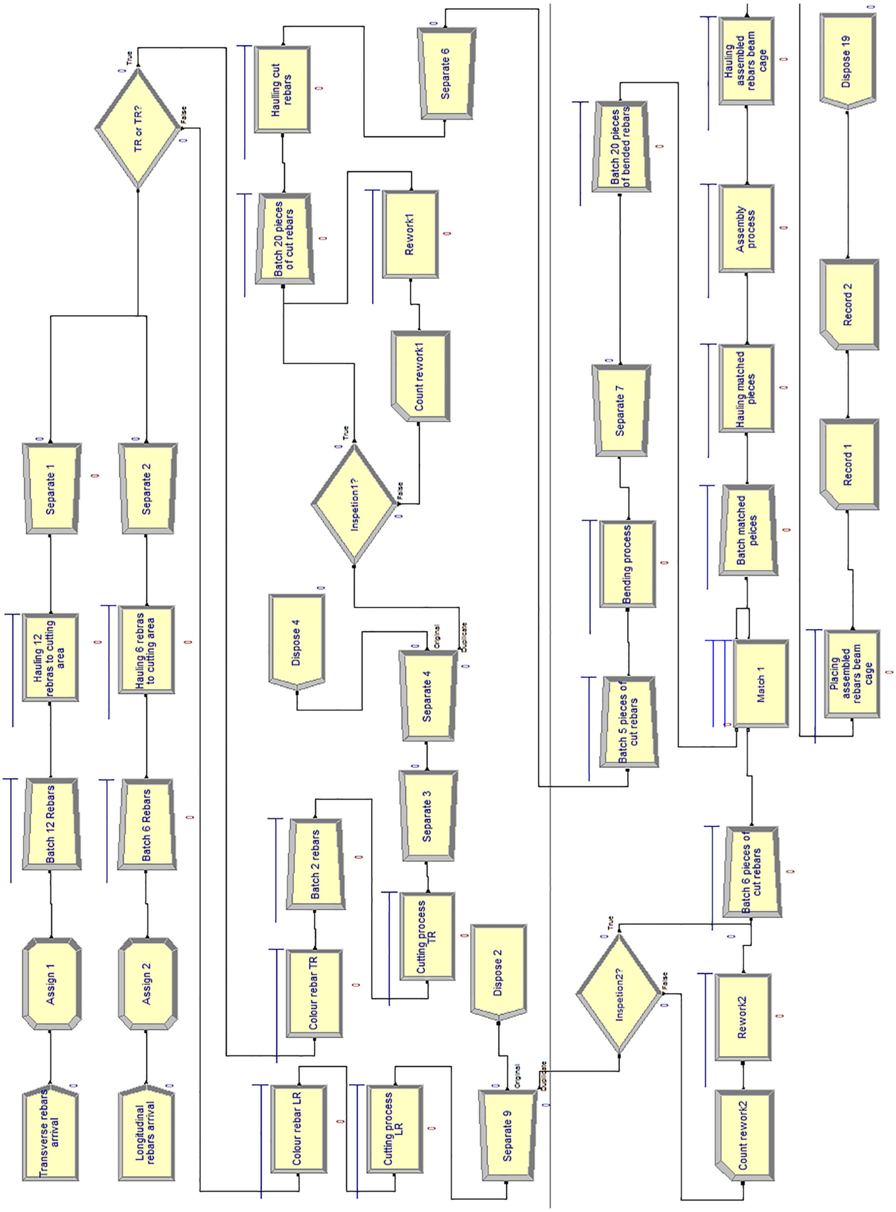


Figure 9.
Lean simulation model by arena

According to (Al-Sudairi *et al.*, 1999; Diekmann *et al.*, 2004; Esquenazi and Sacks, 2006), the lack of polyvalent workers with various technical skills make the process less flexible and reduce productivity. In addition, inefficient resource use contributes to over 10% of the total project cost. To improve the current situation, it seems beneficial to introduce multi-skilled teams, which is a common characteristic of a lean process, into the real-world simulation model to test the potential improvement regarding waste reduction (waiting, inventory) and labor productivity improvement. To do so, a new resources assignment has been implemented, as shown in Table 4. In this case, workers will not have to travel long distances from one workstation to another and the most important the workflow will be accelerated where added-value is created such as (cutting, bending and assembly) because these workstations are now supported by new resources for better process efficiency and balanced flow. It worth mentioning that the new resources assignment was made in coordination with project managers, foremen and engineers in charge of the reinforcement process various. Obtaining the most appropriate allocation of resources was based on the results of the lean model as it was tested for various combinations. Hence, several possible combinations have been proposed before getting to an optimal distribution that takes into consideration the following factors: (1) labor utilization rate; (2) distance travelled; (3) availability of tools to ensure an additional resource.

6.2 Pull value

6.2.1 Reduced batch size. In each workstation in the reinforcement process, it has been observed that rebars are accumulated in large batches and then delivered together to the following work area. This implies that workers spend a lot of time cutting the rebar and transporting them to the next workstation (e. g. bending area) and the same problem continues to occur. This is a sign of the push flow since the upstream workstations are supplied with more material than necessary. In addition, when the upstream workstations are in use, the downstream workstations are inactive which not only produce more inventories but also increase waiting time and minimize workers' use. This approach does not allow entities to proceed simultaneously through the reinforcement process which negatively influences the overall performance (for instance, labor 5 and foreman wait on average 110 and 125 min respectively to receive their first supplies). As previously explained, under lean

Resources assignment Reinforcement activities	Real-world model	Lean model
Hauling TR to cutting area	Labor 1	Labor 1
Hauling LR to cutting area	Labor 2	Labor 2
Color rebar TR	–	Labor 1
Color rebar LR	–	Labor 2
Cutting process TR	Labor 3	Labor 1
Cutting process LR		Labor 2
Rework TR	–	Labor 1
Rework LR	–	Labor 2
Hauling cut rebars TR	Labor 1	Labor 3
Bending process TR	Labor 4	Labor 3, Labor 4
Hauling matched pieces	Labor 2	Labor 4
Assembly process	Labor 5	Labor 5, Foreman
Hauling assembled rebars beam cage	Labor 2	Labor 5, Foreman
Rework of defected cages	Foreman	–
Placing assembled rebars beam cage	Foreman	Foreman

Table 4. Resources assignment in real-world model and lean model

production, the pull concept considers downstream workstations as the direct consumers of the upstream workstations and their supply requirements must be fulfilled as soon as possible with the right amount of materials or parts.

To introduce the pull concept to the observed process, the batch sizes in cutting and bending areas are decreased. For TR, this is applied by reducing the batch sizes of the modules "Batch 100 pieces of cut rebars" and "Batch 100 pieces of bent rebars" in the real-world model from 100 to 20. Similarly for LR, the batch size of the modules "Batch 36 pieces of cut rebars" was reduced from 36 to 6. Working and delivering small batches prevents the accumulation of a large quantity of reinforcing bars in the work areas and provides workers with the amount they just need to perform their tasks.

6.2.2 Optimized resources priorities. The downstream activity requirements should be satisfied in a timely manner and they are regarded as customers of the upstream activity. These requirements may be information, workers, materials, etc. According to (Nikakhtar *et al.*, 2015), if various activities need a common resource, the one that is closer to the end of the work process (downstream activity) receives a higher priority for resource use.

In the real-world model, all activities are given the same priority which is not adequate to implement the concept of traction in the model. To pull value, the priorities for reinforcement activities were set in such a way to allow downstream activities to be performed before upstream one in case they share a common resource. Such improvement leads to a decreased waiting time which in turn enables more rapid delivery of final products. As an illustrative example, as described before in the resources assignment section, labor 1 is supposed to perform three activities: "Hauling TR to cutting area," "Colour rebars TR," and "Cutting process TR." Since the "Cutting process TR" and "Rework TR" activities are closer to the end of the process compared to "Hauling TR to cutting area," "Colour rebars TR," they were assigned a higher priority. Hence, if these activities need labor 1 at the same time, the labor whether cuts the rebars or do rework and then he can be released to perform the rest of the tasks. In this case, the activity "Cutting process TR," which is a prerequisite for other activities, is performed faster and the requirements of downstream activity such as bending and assembling process are timely satisfied. This example is also valid for labor 2. Table 5 shows the priority for each activity in both the real-world and lean models. As presented, the lowest priority is "1" and the highest one is "3."

Table 5.
Priorities of reinforcement operations in real-world model and lean model

Reinforcement activities	Real-world model	Lean model
Hauling TR to cutting area	2	1
Hauling LR to cutting area	2	1
Color rebars TR	–	2
Color rebars LR	–	2
Cutting process TR	2	3
Cutting process LR	2	3
Rework TR	–	3
Rework LR	–	3
Hauling cut rebars TR	2	1
Bending process TR	2	2
Hauling matched pieces	2	3
Assembly process	2	1
Hauling assembled rebars beam cage	2	2
Rework of defected cages	2	–
Placing assembled rebars beam cage	2	3

6.3 Pursue perfection

6.3.1 Increased transparency. As previously explained, increased transparency is one of the main objectives to pursue perfection. Transparency of the process can be described as the extent to which a construction process (or its sub-processes) can effectively communicate with people (Tezel *et al.*, 2010). According to (Sacks *et al.*, 2009), this technique could bring numerous benefits relevant construction process: (1) Positively impacts motivation; (2) enhance workforce involvement in continuous improvement initiatives by enabling rapid understanding and intervention to address problems; (3) The availability of workplace information increases the efficiency of planning and control; (4) decrease the susceptibility to errors, especially in poorly organized workstations.

In the observed process, transparency and the organization of workstations are absent and there is little awareness of this technique among operators. Due to these performances, the reinforcement process is started later than initially planned. Based on the collected data, the preparation of workstations at the beginning of the working day took on average 29.20 min (an average of 30 data points).

Preparation J-1, which is a lean construction tool, aims to achieve a better workers' productivity with less effort and stress through increasing process transparency (Dupin, 2014). At the end of the day for about 15 min, the equipment and materials required for the next day are verified and prepared. The team on site is thus directly operational the next day, without any loss of time. In addition to preparation J-1, 5S and visual management were also applied in the inventory of reinforcement rebars to sort longitudinal rebars (LR) from transverse rebars (TR) and mark their emplacements with visual signs. Hence, the time spent on searching for materials will be significantly reduced. As a result, the application of such techniques in lean simulation model will help in reducing the time dedicated to preparing stores and workstations at the beginning of each working day. It is worth noting that these improvements may lead to other benefits such as better motivation, fewer safety accidents, fewer defects due to improper storage. However, these effects cannot be quantified through a simulation approach.

7. Results analysis and discussions

After applying lean construction principles to the real-world simulation model that leads to a lean simulation model, it is time to assess the impact of this approach on improving the performance of the reinforcement process. To do so, labor productivity, process efficiency and cycle time of the real-world simulation model were computed and compared with the lean simulation model. Table 6 summarizes the results of the comparison. These performance measures are detailed separately in the following sections.

7.1 Labor productivity

A simple and accurate performance indicator for comparing construction processes is productivity (Dunlop and Smith, 2014; Forsberg and Saukkoriipi, 2007). According to

	Labor productivity (Kg/man-hour)	Process efficiency (%)	Cycle time (min)
Real-world model	13.95	7	303.69
Lean model	19.66	8	253.52
Improvement (%)	41	14	17

Note(s): The results were calculated based on the average of 10 replications for both the real-world and lean model

Table 6. Performance measures in real-world model and lean model

(Al-Sudairi, 2007), productivity measurements are crucial to assess waste and can be mutually complementary. On the other hand, a better productivity rate of labor will automatically be reflected in an improved value-added rate, which reduces waste and decreases production costs (Forsberg and Saukkoriipi, 2007). Productivity takes into consideration the inputs and outputs of the studied process. In the construction industry, considering labor as the sole input is commonly used (Abbasian-Hosseini *et al.*, 2014; Nikakhtar *et al.*, 2015). Labor productivity is the fundamental factor affecting the productivity rate due to the nature of the reinforcement process. Considering that work hours are considered as input. Hence, the equation is defined as:

$$\text{Labor Productivity} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Installed quantity}}{\text{Actual work hours}} \tag{1}$$

Table 7 shows models simulation outputs that were used to calculate and compare the labor productivity for both real-world and lean models.

As listed in Table 7, the labor productivity of the real world bricklaying process is 12.21 kg/man-hours. This amount was increased to 17.20 kg/man-hours in the lean simulation model with an improvement of 41%. These results are justified by an increase in outputs which is the installed quantity of beam cages. Considering the same resources (six labors), in each working day, an average of nine additional beam cages are assembled and installed in the lean model compared to the real-world model which will leads to the total process time to be decreased. As could be seen in Figure 10, labor 1, labor 2 and Foreman are underutilized with an average labor use rate of 20%, which means that these workers were inactive for most of the working time (around 384 min of idle time). On the other hand, labor 3 was overloaded with a labor use rate of 94%, which indicates an unbalanced use of resources in the reinforcement process under study. After applying lean construction principles, the workload

	Daily production (beam cage)	Labor productivity (beam cage/ man-hour) *	Labor productivity (kg/ man-hour) **
Real-world model	22	0.46	12.21
Lean model	31	0.65	17.20
Improvement (%)		41	

Note(s): * The inputs is considered the number of assembled beam cages; ** The input is considered the weight of assembled beam cages (Each beam cage weighs 26.64 Kg)

Table 7.
Labor productivity in real-world model and lean model

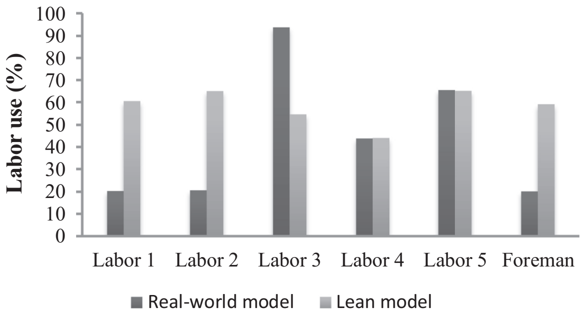


Figure 10.
Labor use in real-world model and lean model

between employees has become more balanced (labors' use rates range between 40% and 65%), as could be seen in Figure 10. Adopting a multi-skilled work team ensured that each labors could perform different tasks rather than one specific task which allows better use of resources and, therefore, a better labor productivity. This is in accordance with the results obtained by Abbasian-Hosseini *et al.* (2014); Bamana (2018); Nikakhtar *et al.* (2015) as they confirmed that effective use of labor's time is the main factor leading to better labor productivity in construction.

7.2 Process efficiency

Efficiency is a key performance factor in measuring the performance of the construction process (Abbasian-Hosseini *et al.*, 2014). The objective of assessing efficiency through a defined process is to achieve better performance by focusing on value creation and non-value elimination (Diekmann *et al.*, 2004). According to (Jørgensen, 2006; Khanh and Kim, 2014), an increase in process efficiency contributes in reducing total project costs with 15%. Under Lean Construction, the process efficiency is defined as the ratio of time spent on VA activities to total cycle time (Al-Sudairi, 2007), as shown in Eqn (2).

$$\text{Process efficiency} = \frac{\text{Time of value adding activities}}{\text{Total cycle time}} \tag{2}$$

As shown in Table 6, the efficiency of the reinforcement process increased to 14% in the lean simulation model. This is the direct outcome of applying lean principles to the real-world model, which resulted in better process efficiency. Whereas the specific impact of each implemented Lean principle cannot be listed separately, it is clear that the above-mentioned improvements have shortened the non-value-added time, especially with regard to waiting time which will be explained in more in next section. Indeed, these simple and free improvements have led to improved process efficiency even though it's not very high (8% in lean model). The low process efficiency in the studied process even in the lean simulation model is due to the nature of this process. This also indicates that many non-value adding activities still exist in lean model such transport of materials, waiting time and rework. There are many additional techniques, which are beyond the scope of the current study, for which value-added operations, such as cutting, bending and assembling, can be improved by more efficient working tools as well as transport and repair operations, which leads to an increase in the time allocated to value-added and reduces the time with no value-added.

7.3 Cycle time

Reducing cycle times not only results in timely project completion but can also leads to increased process efficiency and improved labor productivity (Abbasian-Hosseini *et al.*, 2014; Al-Sudairi, 2007; Nikakhtar *et al.*, 2015). Therefore, it seems appropriate to compare the cycle times between the real-world simulation model and the lean simulation model.

As shown in Table 6, there is 17% reduction in cycle time after lean construction principle have been applied in the original process. The cycle time of the reinforcement process is shortened in the Lean model due to the reduction of non-added value creation, which makes the process leaner and faster. Table 8 is presented to better identify and measure improvement in each type of operation (VA or NVA); therefore, the component with the highest effect on cycle time reduction can be highlighted. As could be seen from Table 8, simulation outputs illustrate 94% share of NVA & NVAR activities in the original reinforcement process, which was a good motive for testing lean construction principles. Applying lean construction principles to the original reinforcement process leads to 18% reduction in NVA & NVAR activities, 3% improvement in VA activities, as shown in Table 8.

It is worth noting that waiting times and NVA (rework, transport, etc.) are shown separately to illustrate the predominant share of waiting times.

Waiting times hold a dominant share in NVA & NVAR activities (87% in both real-world and lean model). This is in accordance with the study carried out by (Diekmann *et al.*, 2004; Nikakhtar *et al.*, 2015) and which confirmed that the dominant share of waiting time is due to the nature of the reinforcement process. For more clarification, waiting time comparison (in each activity) between the real-world model and the lean model is illustrated in Table 9. This table shows that after applying lean construction principles, waiting time in most activities is reduced to less than one minutes in lean model compared to original activities in real-world model (e.g. cutting process TR: 34.47 min, cutting process LR: 35.89 min, assembly process: 27.96 min, etc.).

8. Conclusions

This research paper aimed at providing a comprehensive and systematic approach for applying lean construction principles in a given construction process, reinforcement process, using simulation modelling. This is achieved through the development and improvement of the reinforcement activities using ARENA, which leads to a leaner process (lean simulation model). The current study started with a field study based on two lean construction principles: (1) specify value and (2) map the value stream which to better understand the logic and the flow of the process under study. Based on the process map as well as the best-fitted

Table 8.
The share of VA and NVA activities in real-world model and lean model

		NVA & NVAR activities		
	VA (min)	Waiting (min)	Rework, transport, and NVAR	Cycle time
Real-world model	19.77 (6%)	263.97 (87%)	19.95 (7%)	303.69
Lean model	20.27 (8%)	219.46 (87%)	13.79 (5%)	253.52
Improvement (%)	3	17	31	17
		18		

Note(s): The results were calculated based on the average of 10 replications for both the real-world and lean model

Table 9.
Waiting time in real-world model and lean model

Waiting time Reinforcement activities	Real-world model (min)	Lean model (min)
Hauling TR to cutting area	0.77	0.00
Hauling LR to cutting area	0.36	0.00
Color rebar TR	–	2.51
Color rebar LR	–	1.30
Cutting process TR	34.47	0.03
Cutting process LR	35.89	0.30
Rework TR	–	0.19
Rework LR	–	0.01
Hauling cut rebars TR	3.38	0.60
Bending process TR	7.82	0.75
Hauling matched pieces	4.74	0.01
Assembly process	27.96	0.02
Hauling assembled rebars beam cage	0.26	0.10
Rework of defected cages	0.00	–
Placing assembled rebars beam cage	0.03	0.19

distributions for each activity the developed model (real-world model) was tested, verified and validated. Subsequently, applying three lean construction principles including "Make value flow," "Pull value," and "pursue perfection" to the original reinforcement process leads to 41% improvement in process productivity, 14% enhancement in process efficiency and 17% reduction in cycle time. Mistake-proofing concept, multi-skilled labors, reduced batch size, optimized resources priorities and increased transparency are powerful techniques to achieve a leaner process, especially if they are applied simultaneously. The costs of these techniques will always be more economical compared to the benefits of lean construction principles.

The current research demonstrates the advantages of implementing lean construction principles by providing a numerical scientific basis for verifying the potential for improvement in the performance of construction processes. Hence, the quantitative analysis of the study helps convince more contractors of the profitability of applying lean construction principles in construction processes. The findings and discussions of this work provide guidance for construction managers since they suggest many improvements aiming at enhancing the performance of a construction process, reinforcement process, by applying five lean principals (identify the real value; map the value stream; flow; pull; and perfection) and conventional simulation modelling steps (data collection and fitting of activities duration; model testing/validation/verification; model improvement). The time wasted during non-value added activities such as waiting, transportation and rework must be optimized. Several techniques have been proposed by the authors for waste reduction such as poke-Yoke, pull, reduced batches, load balancing for workers, 5S, visual management and J-1. In summary, this paper is a contribution to a deeper understanding of main sources of wastes affecting the performance of construction process, which can be beneficial to construction project managers from others developing countries facing the same waste factors and having similar socio-economic cultural aspects. Furthermore, this work brings an original methodology that could help practitioners, companies and researchers to support decision making process by analyzing different lean construction scenarios and assessing their impacts on performance outcomes of any construction process before real-world implementation. Finally, it is important to consider that, although this study focuses on a specific construction process, it can be anticipated that construction operations have a high potential for improvement by applying lean construction principles and simulation, which will ultimately lead to drastic promotion in performance of construction projects.

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Appendices

Appendix 1

Figure A1.
Simple representation of reinforcement operations

Appendix 2

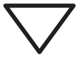
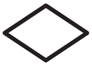
Symbol	Title	Function
	Inventory	Inventory of raw materials or other components.
	Transport	Transportation of work-in-progress, parts, or finished products between work stations.
	Operation	An operation with an impact on the inputs; may be a VA activity or a non-value added activity.
	Decide	This module allows making decisions on the basis of on probabilities, entities types, and so on.

Table A1.
Brief Description of (OPC) symbols (used in process mapping)

Module	Symbol	Function
Create	 Create	This module is designed to provide the starting point for entities in a simulation model. Entities are based on a time interval between arrivals. The type of entity can be defined in this module.
Batch	 Batch	Entities coming to the Batch module are queued until the specified number of units is accumulated
Decide	 Decide	This module allows making decisions on the basis of on probabilities (e.g., 95% true; 5% false), entities types (TR or LR), and so on.
Separate	 Separate	This module may be used either to duplicate an ingoing entity into several parts or to separate a previously batched entity.
Process	 Process	This module is intended to depict various types of activities: value added, non-value added.
Match	 Match	This module groups a defined number of pending entities in different queues and, then, released as one entity.
Assign	 Assign	This module is designed to assign new values to entity attributes, variables, entity types, entity images or other types of variables. Several assignments may be made with a unique Assign module.
Record	 Record	This module is designed to gather statistical information from the simulation model.
Dipose	 Dispose	This module is designed as the end-point for entities in simulation model.

Table A2.
Brief description of ARENA modules

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