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Verification of Lean Construction Benefits through Simulation Modeling: A Case Study of Bricklaying Process

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Abstract

The construction industry includes a large number of specialized areas and disciplines, most of which are based on cyclical processes during the construction phase. With the introduction of the lean construction concept, researchers have begun to apply lean principles to construction processes. The research described in this paper applies lean principles to a construction operation using computer simulation. Simulation makes it possible to evaluate the effects of implementing lean principles into construction processes prior to real world application. A case study of the bricklaying process was conducted to quantify and evaluate the results of applying lean principles. Data required for constructing the simulation model were gathered from the construction site through work and time study techniques. Preliminary results show improvement opportunities exist in the bricklaying process due to a high share of non value-adding work. The results of lean principles implementation also reveal that lean principles can enhance the performance of the bricklaying process through more than 40% productivity improvement.

Keywords: *lean construction principles, simulation modeling, labor productivity, performance improvement*

1. Introduction

The construction industry is a slow growing industry with frequent problems such as low productivity, poor safety, time overruns, insufficient quality, etc. (see Koskela, 1993; Senaratne and Wijesiri, 2008). Construction attributes (such as uniqueness, site production, complexity, quickness, etc.), also increase uncertainty and variability, which make the above-mentioned problems worse.

Some researchers believed that although lean production theory was established for manufacturing industry, the similarities between the construction processes and craft manufacturing make lean production theory very applicable to construction (Farrar *et al*., 2004; Mao and Zhang, 2008). Hence, success of lean principles in manufacturing industry on one hand and need to overcome the aforementioned problems on the other hand, motivated construction management researchers to apply lean production principles to the construction industry. These efforts led to the development of a “lean construction” philosophy.

Many studies have been done in the field of lean construction and they prove that this theory holds a significant potential for improvement in construction projects. However, a review of the literature shows that most of research is dedicated to the subject of scheduling and controlling while only a few studies can be found in evaluating the application of lean principles into construction processes during the construction phase. Ballard and Howell (1994), Tommelein (1997), Al-Sudairi (2007) and Wang *et al*. (2009) are those researchers who improved the performance of their desired processes through applying lean principles. In addition, Mao and Zhang (2008) in their case studies reached more productivity through reengineering and implementing the lean principles.

The goal of this paper is to apply lean principles to construction processes on a given project. This issue is explored by focusing on a case study of the bricklaying process. Computer simulation and modeling tools were also utilized in order to eliminate the cost of a real experiment and provide precise and detailed calculation.

2. Lean Construction: Design Construction Processes for Flow and Value

According to Koskela (2000), construction is primarily managed based on the transformation view. In this view, a construction process or sub-process is assumed to be a conversion of inputs to an output. The value of the output and the cost of total process are only affected by the value and cost of inputs, respectively (Abdel-Razek *et al*., 2007). Therefore, in order to improve the construction process in this view, attention must be focused on the inputs of the process and as a result, managers neglect flow principles and value generation concepts largely. Consequently,

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it causes value loss and considerable waste in construction processes (Koskela, 2000; Abdel-Razek *et al*., 2007). This issue constitutes the basis of lean concepts. The main argument of the lean construction concept is that processes need to be analyzed not only as transformations but also as flows and value generation. In other words, lean emphasizes the consideration of flow and value generation in designing construction processes in order to achieve a lean process. The basic ideas of lean related to processes in the construction phase are discussed in three categories: (1) Flow production (2) Value generation and (3) Just-in-time delivery in construction processes.

2.1 Flow Production Concept in Construction Processes

Construction processes usually include various on-site activities performed sequentially or in parallel with a complex interaction between materials, equipment and labor (Larsson, 2008). Traditional thinking of construction generally improves the processes by concentrating on promotion of conversion activities (Conversion activities are those that transform raw materials or information to the final product occurred in them. Other activities such as inspection or transportation are called flow activities (Koskela, 1993)). separately. However, there are many improvement opportunities through effective management of flows between conversions (Ballard and Howell, 1994). For instance, waste in construction is generally assumed to be physical, such as waste of materials in the construction processes, but there are multiple activities that are not value adding (such as inspection, delays, transportation of materials, waiting time, etc.) and should be considered process waste (Senaratne and Wijesiri, 2008). The Flow view of construction processes enables construction managers to improve their activities by recognizing and reducing these kinds of waste.

In lean systems, the flow view of processes is defined as movement of materials, information, and equipment through a system (Womack and Jones, 1996). Lean construction theory makes flow of materials or information in a construction process similar to a production line in manufacturing. In fact, flow view describes processes as being composed of not only transformations, but also inspection, waiting, and moving of information, materials, and equipment. Therefore, it provides an environment in which improvement chances are exposed. It can be said that flow view of construction processes is a prerequisite for applying lean principles.

2.2 Value Generation

Concentrating on the value, which is transferred to the final product, is another basic aspect of lean construction. From a lean perspective, the activities in the physics of workflow can be classified as Value-Adding (VA) and Non Value-Adding (NVA). In contrast to the NVA, VA activities are those that directly affect the production of the final product, increase the economic worth of a process and are valued by the customer. To be thorough, Koskela (1993) divided various construction activities into two categories: conversion and flow activities. Conversion activities are defined as those that convert raw materials or information into a final product while flow activities are specified as linkages between conversion activities (such as inspection, waiting, moving, etc.). Flow activities do not themselves contribute value to the final product. While all activities take time and are costly, only conversion activities generate value for a product (Koskela, 1993). Therefore, conversion and flow activities are respectively recognized as VA and NVA activities. Lean construction attempts to redesign the processes in order to achieve two goals: (1) Eliminating or minimizing the share of NVA activities; and (2) Enhancing the labor's time consumed on VA activities. As explained before, the flow view of construction processes makes it easier to identify VA and NVA activities by exposing opportunities to enhance the transferred value.

2.3 Just-in-time Delivery (Concept of Pulling)

According to Thomas *et al*. (2002), undesirable delivery of materials (not at the right time or right place) is one of the most common problems in construction projects. Delay in providing materials or in completing a prerequisite task keeps labors and equipment waiting. This problem decreases the labor productivity and extends the cycle time of processes (Tommelein, 1998). Material availability is also one source of uncertainty that can result in many stoppages, which in turn lead to increase of project duration (Al-Sudairi, 2007). Furthermore, other research has shown that labors slow their working pace and become demotivated when an adequate supply of materials is not available (Thomas *et al*., 2002). On the other hand, supplying the downstream's requirements (material) prior to demand, generate unnecessary inventories and it may cause extra cost. Hence, it can be concluded that the supply of material is one of the main factors, which is very effective in completing the construction processes (Tommelein, 1998).

Another basic concept of lean production is "Pulling" which aims to ensure just-in-time coordination between upstream and downstream tasks. The origin of pulling concept is based on the idea that the upstream does not produce a product or service until it is required by the downstream (Womack and Jones, 1996). Therefore, during a construction process (in construction job site), "Pulling flow" is set by using a system of signals from downstream to upstream workstations. This enables the downstream to advise the upstream of their requirements or possible disruptions. As a result, the product (materials and information) is delivered to the next station (downstream) at the right time and the right place and also without delay and unnecessary storages. To be brief, from a just-in-time perspective, inventories and unnecessary storage of materials are not valuable and should be regarded as waste.

3. Literature Review

3.1 Value-adding (VA) and Non Value-Adding (NVA) Activities

Lean construction attempts to improve construction processes via making VA activities more efficient and eliminating (or at least reducing) the share of NVA activities in a construction process. Supportively, researchers have reported that labor productivity shows noticeable improvement by spending more time on VA activities (Thomas *et al*., 1984).

Some researchers argue that some flow (or NVA) activities are unavoidable and critical due to generating and transferring value to the final product (Zhao and Chua, 2003; Al-Sudairi, 2007; Mao and Zhang, 2008). As a result, the definition of VA and NVA activities depends on the researchers' point of view and given case studies. Even with the existence of such a difference in defining VA and NVA, research proves that the NVA activities hold a considerable share in most of construction processes (see Farrar *et al*., 2004; Dunlop and Smith, 2004; Al-Sudairi, 2007; Christian and Hachey, 1995; Agbulos and AbouRizk, 2003), exceeding 50% in some cases (see Agbulos and AbouRizk, 2003; Christian and Hachey, 1995; Al-Sudairi, 2007). Although some of NVA activities are sometimes necessary and even are required for carrying out an operation (Mao and Zhang, 2008; Zhao and Chua, 2003), a high percentage of their share has strong potential for construction process optimization.

3.2 Process Simulation and Lean Construction

It can be seen that the construction industry has historically shown resistance to change (Farrar *et al*., 2004). In reality, while the results of applying new methods are not exactly visible prior to real experimentation, justifying contractors to implement the new practices can be challenging. The same discussion occurs when one wants to apply lean principles to construction processes. For this research, computer simulation provides an excellent environment to implement the lean principles, study their effects, and gain a better understanding of how these principles perform. Halpin and Martinez (1999) also believed that because most construction operations have a natural cyclic manner, they have a high improvement potential using simulation.

Computer simulation is defined as the process of making a mathematically and logically explained model of a real world system (Farrar *et al*., 2004). Simulation provides a virtual world for decision makers to better understand the nature of the problems by conducting experiments in a more cost effective (no cost of real-world trial and error) and controllable environment (Wang and Halpin, 2004; Mao and Zhang, 2008). Real world processes can be efficiently modeled and examined from an application perspective using simulation. Therefore, the concepts of lean construction can be tested and validated via computer simulation prior to actual field implementation (Halpin and Kueckmann, 2002; Wang *et al*., 2009).

Literature review also demonstrates that simulation has proven to be a powerful tool to model and analyze construction processes (see Alkoc and Erbatur, 1997; Tommelein, 1997; Farrar *et al*., 2004; Sacks and Goldin, 2007; Hassan and Gruber, 2008; Mao and Zhang, 2008; Wang *et al*., 2009). For instance, Tommelein (1997) evaluated the concept of pulling in pipe-spool installation process via simulation. Simulation was also used for the design and optimization of the concrete delivery and pouring process (see Alkoc and Erbatur, 1997; Hassan and Gruber, 2008).

In general, the simulation of construction operations requires a tool that provides an experimental environment, which does not need to be supplied with input of numerous amounts of data (Halpin and Martinez, 1999). In addition, due to computer advances in graphical techniques, there is a trend to use graphical methods for process simulation and model development (Zhang *et al*., 2005). *CYCLONE* (Halpin, 1977), *CIPROS* (Tommelein and Odeh, 1994), *STROBOSCOPE* (Martinez and Ioannou, 1994), *ABC* (Shi, 1999) and *SIMPHONY* (Hajjar and AbouRizk, 1999) are some simulation tools implemented more by researchers in construction area.

One of the general simulation tools in this regard is *ARENA* (introduced by Takus and Profozich in 1997). *ARENA* is a generic discrete-event simulation language with a powerful graphical interface. It consists of module templates, constructed around *SIMAN* language patterns and other facilities, and augmented by a visual front end (Altiokand Melamed, 2007). Overall, *ARENA* makes it easier to model uncertainties relative to duration and timing, resource assignment, quantity and flow path. Therefore, it is used for simulation in this paper.

4. Research Methodology

This section shows how the rest of the paper is organized. Fig. 1 shows the adopted research methodology to make a valid simulation model for analyzing lean applications. First, for simulating the construction process (bricklaying process), the actual behavior of the bricklaying process must be precisely examined to provide an empirical basis. This was completed through detailed observations, process mapping and discussion with the practitioner. In the second step, data were collected during construction, and then were used to determine Probability Density Functions (PDF) for the activity's duration. Third, the model was constructed using computer simulation according to the bricklaying process map and PDF of activity duration. Fourth, to test the accuracy of the simulated model, the developed model was verified and validated against the real world. Also, required modifications were conducted to solve the inconsistency of the model and real world. Fifth, after validation, the real world model was redesigned to implement selected lean principles. Introducing the lean principles to the real world model led to a new model, which is called the lean model. Afterwards, the performance of the real world and lean model was exactly measured based on cycle time, productivity and process efficiency, and in the final step, the comparison between their outputs was done to evaluate the results of the applicability of lean concepts in construction processes. The improvement of value-adding labor working time has been investigated by others (Farrar *et al*., 2004; Dunlop and Smith, 2004; AbbasianHosseini *et al*., 2012 (AbbasianHosseini *et al*. (2012) examined the improvement of the ratio of value-adding activities to non-value adding activities in a basic brick work operation (single-wall

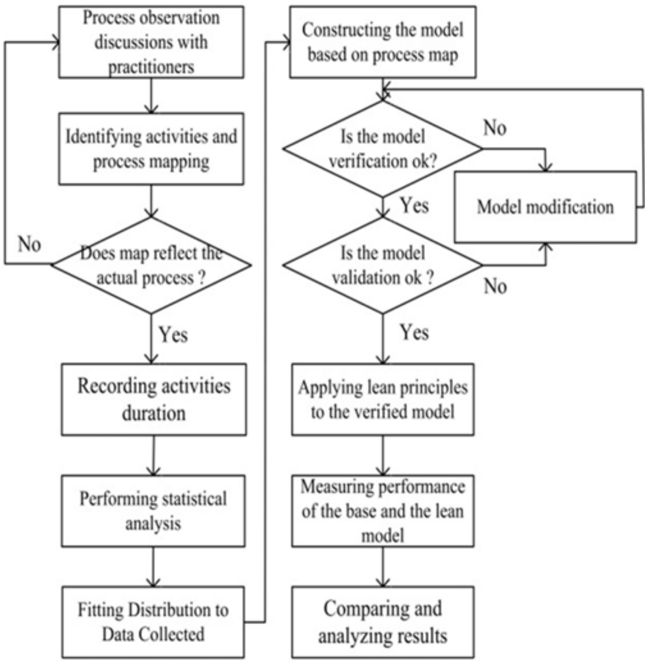

Fig. 1. Research Methodology Flowchart

process) by implementing three basic principles of lean construction, Simplification, Optimized utilization of labors and crews, and Just-in-time delivery of materials.)).

5. Case Study: Bricklaying Process

To test and evaluate the applicability of lean principles in construction processes, an actual experiment is required. Therefore, this study extends the issue of lean applicability to construction by focusing on a bricklaying process of a six-floor trade complex located in Mashhad, Iran. A subcontractor was responsible for completing the task of bricklaying, which includes bricklaying of all 192 external walls of the building (32 walls for each floor). All the walls are 3.2 meters high and 4 or 6 meters wide (sixteen of each). According to the basic schedule, the contractor was to complete the bricklaying task in 50 days.

The schematic layout of the common bricklaying process was obtained through personal observations and video recordings (Fig. 2). Two foremen and five labors dealt with the task of bricklaying. As can be seen in the schematic layout, labor 5 makes the required mortar for placing the bricks. After that labor 3 hauls the mortar to the place where rows of bricks are placed. At the same time, bricks flow through the process. For this flow, Labor 1 fills a bucket with bricks and the bucket is then carried to the working area by a trolley hoist controlled by labor 2. In the working area, labor 4 is in charge of unloading the bucket and carrying the bricks for foreman 1 and 2 who places rows of bricks and spreads mortar, respectively.

5.1 Process Mapping and Data Collection

In the first step toward building a simulation model, activities

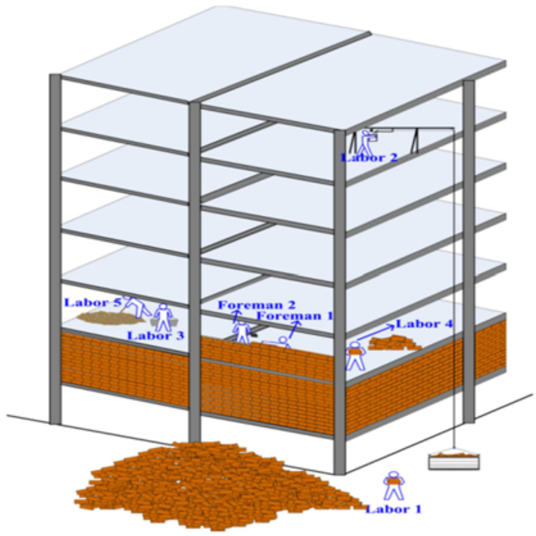

Fig. 2. Schematic Layout of the Conventional Bricklaying Process

of the process and their sequences, labor and resources, and workflow need to be determined based on the bricklaying process in the previously discussed construction project. According to Al-Sudairi (2007), interactions between resources, activities, linkages and the flow of material or information in any construction process can be represented by "process mapping". A process map is a map that visualizes the flow of work and identifies the value stream, which can be illustrated based on the field observations and discussions with practitioners. A preliminary process map was first established based on schematic layout of the process and then refined and validated through discussions with practitioners. Fig. 3 depicts the bricklaying process map based on two main flows, i.e., mortar and brick. This figure is illustrated by using Operation Process Chart (OPC) symbols (OPC symbols are explained in Appendix A). It is worth mentioning that a process map not only is important for effective development of the simulation model but also has great importance in how to implement lean principles, i.e. it enables visualization of the work process flow.

A simulation model uses a random duration for each activity, which should be chosen from a specific data set. Hence, after having the logic of process flow diagram completed, it is time to determine quantitative data (related to each activity) for inputs of the simulation model. A detailed comprehensive field survey was conducted via time and work-study techniques to gather this quantitative data. The techniques were based on filming the total bricklaying process and then measuring duration times for each activity.

Modeling a random process is usually performed by selecting and fitting PDF to elements of that process based on sample data. According to Law and Kelton (2000), to develop a reliable simulation model, using the best-fitted distributions is more efficient than relying on empirical data. Empirical data are just able to create values based on what is observed, while there would be a lot of ingenerated value with a high tendency to be

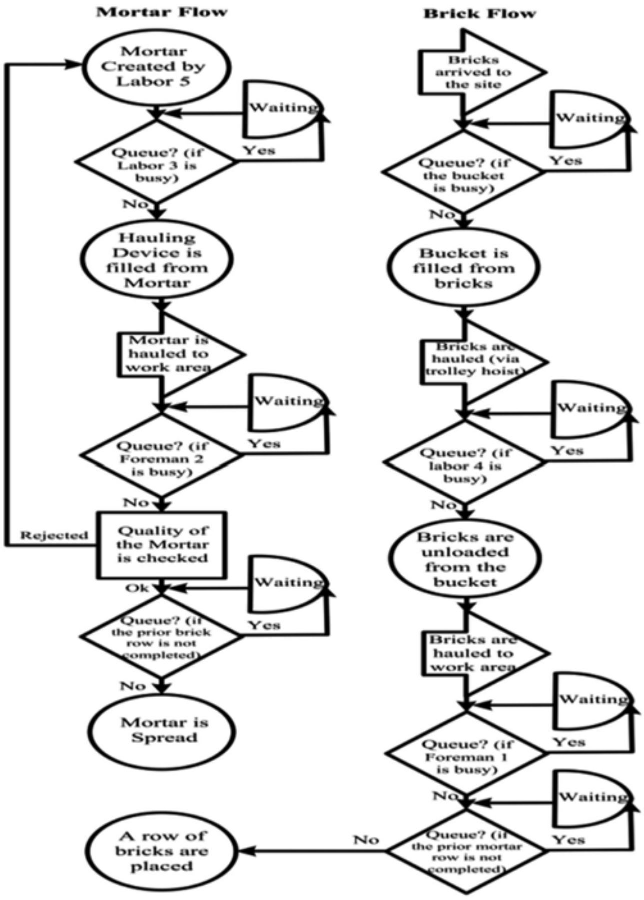

Fig. 3. Process Map of the Bricklaying Process

generated. Furthermore, one may find irregularities in this empirical distribution (Al-Sudairi, 2007). Therefore, best-fitted distributions of data were used instead of empirical distributions for simulated process.

Various software packages are used to fit a distribution to a sample data. The accessibility of such packages makes this process quick, easy and accurate (Al-Sudairi, 2007). EasyFit is a commercial package used in this study that fits a wide variety of distributions to sampled observations. As an example, the process of selecting the most suitable distribution of the activity "Fill the Bucket by Labor1 in 4-meter wide wall" is explained. To do so, 30 data points (The number of observations was calculated based on work and time study techniques.) were observed for the duration of the activity through reviewing videotapes recorded on the construction site. Using EasyFit, 24 continuous distributions (such as Exponential, Beta, Gamma, Uniform, etc.) were tested against the collected data, and the most promising ones according to the goodness-of-fit tests were selected. The goodness-of-fit tests (the chi-square, Anderson Darling and the Kolmogorov-Smirnov) were used to validate the intended distribution. In this case, Weibull distribution seemed to be the most appropriate since none of the mentioned tests reject this distribution (based on Kvam and Vidakovic, 2007). Fig. 4 depicts the histogram of the collected data and the Weibull

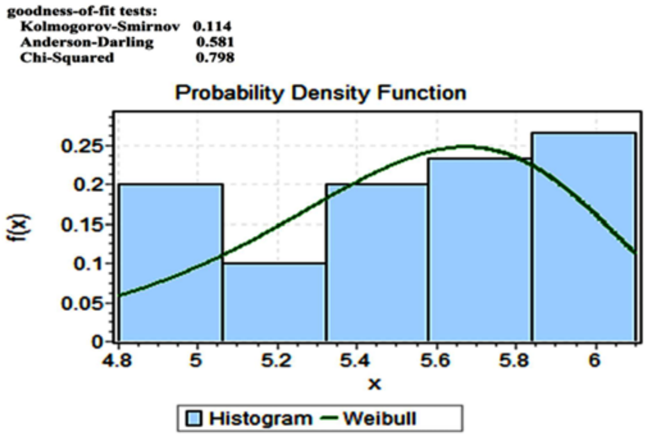

Fig. 4. Comparison between the Measured Data and the Fitted Distribution of the Activity "Fill the Bucket"

distribution (fitted probability curve) fitted to the histogram. The results of goodness-of-fit test are also shown in the figure. Data distribution's parameters in each activity were similarly obtained for both 4 and 6-meter wide walls (see appendix C).

5.2 Simulation Model Development

After finding the best-fitted distributions of activities, the simulation model is developed for the chosen process (bricklaying). The process map, distribution's parameters, and actual behavior observations were used as inputs to accurately model the conventional bricklaying process via ARENA simulation software. Fig. 5 illustrates the simulated model for the bricklaying process. The model consists of various types of modules aim at pushing the model closer to what happened in the real world process (A description of ARENA modules is provided in Appendix B). The figure shows two major flows (brick and mortar flow), corresponding to the process map. As can be seen in the figure, the brick and mortar flows start at create modules named as "Brick Creator" and "Mortar Creator, and finish at dispose modules named as "Finish 1" and "Finish 2".

Some extra modules or linkages were also used to meet the logical aspects of the way the process was completed. For instance, the modules of Batch and Separate were used to model the difference between the quantities of materials processed in two sequential workstations. Furthermore, some modules, such as the Assign module, were only utilized for producing data required in output analysis. However, complete explanation of the construction model is not in the scope of this paper. It should be noted that the 4 and 6-meter wide walls have the same graphical simulation model but their distributions (inputs) are different.

5.3 Verification and Validation of the Model

A process of modeling will be successful when the simulated model accurately depicts the present workflow process and the interrelationships among various tasks. Hence, before any experiments with simulated models, it is essential to verify and

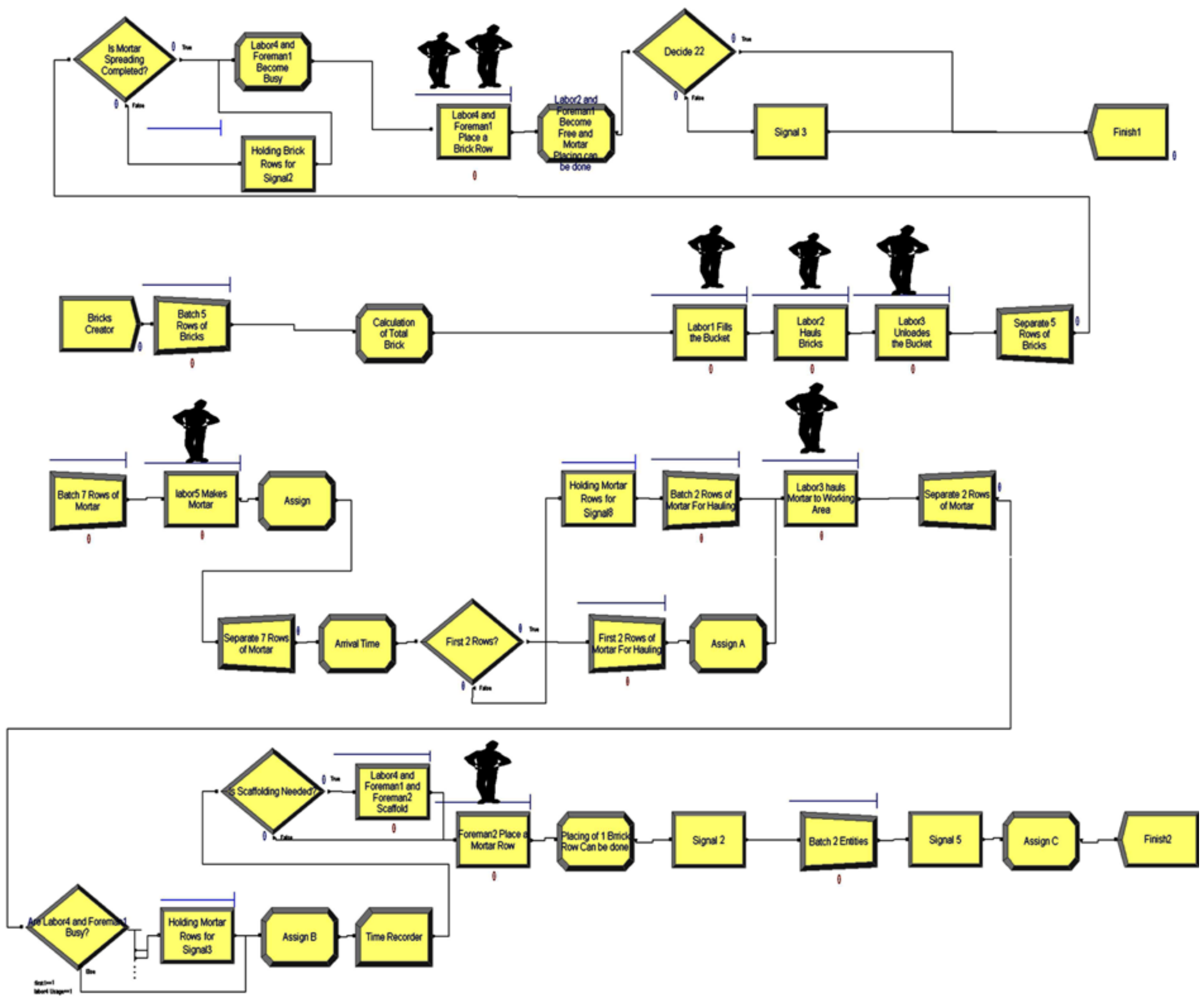

Fig. 5. Simulated Model of Real World Bricklaying Process by *ARENA*

validate these models (Hassan and Gruber, 2008). Model verification ensures that the model behaves as expected and it does not have any logical errors (Al-Sudairi *et al*., 1999; Al-Sudairi, 2007). In fact, verification evaluates the properness of the formal representation of the model by examining computer code and test runs, and measuring consistency based on the model's statistics (Altiok and Melamed, 2007). On the other hand, model validation ensures that the simulated model reflects the actual behavior of the process (Al-Sudairi, 2007). In the validation step, model performance, obtained from test runs, is compared to its equivalent in the real world system in order to assess how realistic the modeling assumptions are. In fact, validation is a critical step to construct a reliable simulation model (Altiok and Melamed, 2007). Several iterations should be run to make the simulated model closer to the actual behavior and reach a verified and valid model.

5.3.1 Model

Verification. Verification, to be more specific, includes 1) inspecting the logic of the model, 2) performing simulation test runs, 3) tracing the entities in sample path trajectories, and 4) evaluating the consistency (Altiok and Melamed, 2007). In verification of the simulated bricklaying process, transactions were checked to ensure they go where they are supposed to go and are doing what they are supposed to do under every condition. For instance, performance verification of the activity 'Labor 5 Makes Mortar' is done through detailed activities' behavior tracing in the model. To be exact, the labor 5's performance results are compared with the total throughput in a random test run of the model (4-meter wide wall). Results of a test run in Fig. 6 demonstrate that labor 5 has been busy in 36.05% of the total process duration (119.17 minutes). It means that, the time that labor 5 has spent on making mortar for all of a 4-meter wide wall construction is equal to 42.96 minutes (0.3605*119.17). On the other hand, according to the documents, labor 5 on average makes mortar corresponding to seven bricklaying rows in 14.5 minutes. Therefore, labor 5 has made mortar 2.96 times (42.96/14.5) in the examined test run, and it is almost equal to Total Number Seized (three times) in the Fig. 6, which shows that our activity's performance could be verified. Similarly, all the transactions, modules, linkages and resources were exactly examined and verified.

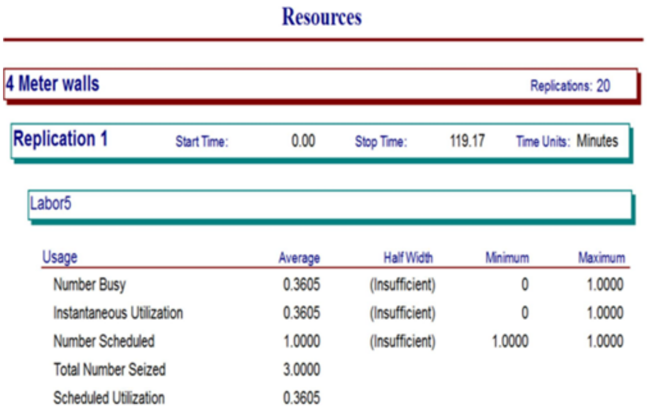

Fig. 6. Results of the Model for Labor5 Performance

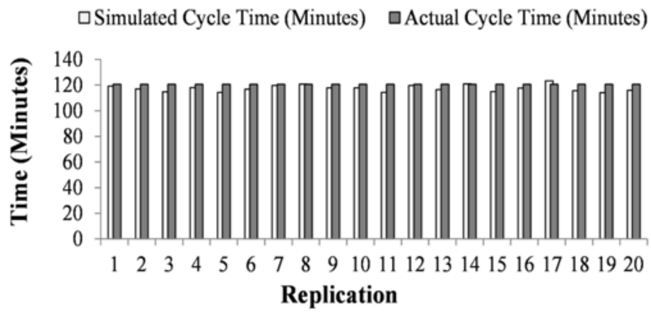

Fig. 7. Validation Result of the Real World Model (4-meter wide walls)

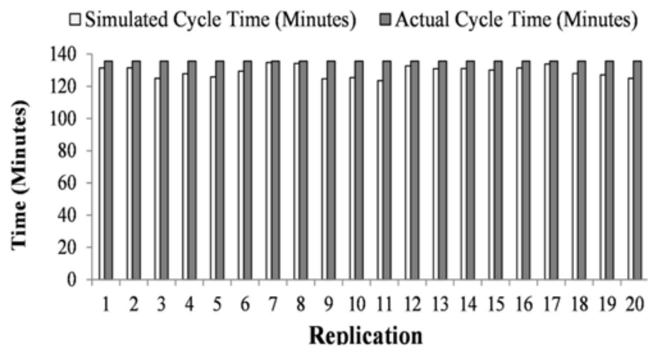

Fig. 8. Validation Result of the Real World Model (6-meter wide walls)

5.3.2 Model Validation

Once the examiner is satisfied with the verification stage, validation activities can get under way. As mentioned before, the standard approach of validation is to compare collected real world data to the simulated model outputs (Altiok and Melamed, 2007). One of the appropriate factors to show how real world process and simulated process are alike is cycle time. According to Krupka (1992), time is useful and universal metric for comparison, because it can be used to generate improvements in cost and quality. Al-Sudairi (2007), Hassan and Gruber (2008) and Wang *et al.* (2009) also compared the cycle times between real world and simulated process in order to validate their model. Therefore, cycle time comparisons were done for validation. After each testing, necessary modifications were done to make the simulated model closer to the real world bricklaying process.

In order to do validation, first, the number of simulation runs to produce the desired level of accuracy should be determined. Generally, in order to produce adequate outputs, a single run of the model is not sufficient (Hassan and Gruber, 2008). Yeh and Schmeiser (2000) suggest that a desired level of accuracy can be achieved by using ten to thirty replications. Hassan and Gruber (2008) also validated their model based on ten replications. Therefore, the number of simulation runs for model validation and other calculations was set to 20 replications.

After determining the number of simulation runs, validation was done for the simulation model. It should be noted that, in the case studied, it is essential not to compare all real world and simulation model outputs correspondingly, because each simulation run does not correspond to a specific real world cycle. Therefore, the average of 20 real world field observations was compared with 20 simulation runs. Final results of the validation are summarized in Figs. 7 and 8. As can be seen, the difference between the average of 20 real world field observations and the 20 replications for both models (4 and 6-meter walls) are less than 5 percent, which is considered acceptable. Now, the simulation model of the bricklaying process is ready for lean principles application.

5.4 Applying Lean Construction Principles to the Model

After constructing and validating the real world model, it is time to apply the previously mentioned lean concepts. Therefore, lean principles applied to the observed process (bricklaying) are explained in three main areas: (1) implementing flow view of production in the bricklaying process; (2) Value generation by improving VA activities and decreasing the share of NVA activities; and (3) Setting up the concept of pulling to decrease labor's waiting time and unnecessary storages.

5.4.1 Implementing Flow View of Production in the Brick-Laying Process

Brick and mortar flow constitute the basis of bricklaying process. These two flows correlate with each other in many aspects (such as "brick placing" and "mortar spreading", which make the modeling process complex. Drawing the bricklaying process map not only clarifies the flow of value to the final product in the process, but also provides a better understanding of relationships between activities, linkages and resources. It should be noted that this concept does not make an improvement by itself and it plays a complementary and basic role to applying other lean principles and techniques. The process map of bricklaying operations is depicted in Fig. 3.

5.4.2 Value Generation by Improving the VA Activities and Decreasing the Share of NVA Activities

The labor's time spent on waiting, VA and NVA activities in the bricklaying process were obtained and tabulated in Table 1.

Table 1. The Labor's Time Spent on Waiting, Value-adding and Non Value-adding Activities

	Total works (man-hours)	VA works (man-hours)	NVA works (man-hours)	
			Waiting	NVA activities
4-meter wide walls	13.71	3.88 (28%)	9.08(66%)	0.75 (6%)
6-meter wide walls	15.07	4.03 (27%)	10.21(68%)	0.83 (5%)

Note: The quantities are calculated based on the average of 20 replications.

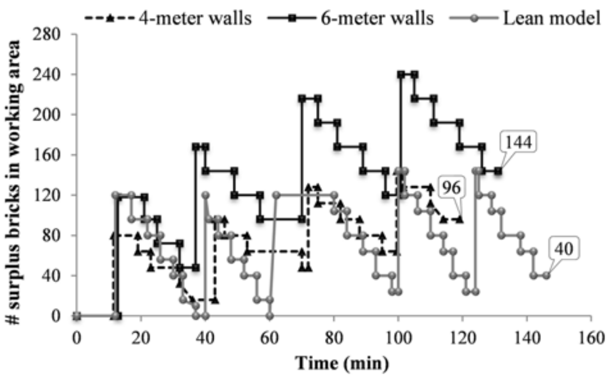

Fig. 9. Comparison of the Surplus Bricks Amount between the Real World and Lean Bricklaying Models at Working Area

NVA activities include "Fill Bucket", "Haul Bricks", "Unload Bucket", "Haul Mortar" and "Scaffolding", while VA activities are "Place bricks", "Make Mortar" and "Place Mortar". NVA activities and waiting times are shown separately to demonstrate the dominant share of labor's idle time. However, both of them do not add value to the final product and are considered to be NVA works. As can be seen in Table 1, more than 70% of the labor's time is spent on the NVA works. NVA works in the bricklaying process are comprised of waiting and NVA activities such as inspections, hauling and storing materials, scaffolding, etc. A high share of NVA work in the process reveals appropriate opportunities for optimization. As mentioned before, lean construction attempts to eliminate or at least minimize the share of NVA works and to increase the labor's time consumed on VA activities. Hence, to achieve a leaner system, the bricklaying process should be designed in a way that laborers spend more of their time on VA activities.

"Waiting" holds a dominant share in NVA works (more than 66%). Through closely reviewing the real world model results, it was understood that one of the main factors that causes waiting is the nature of bricklaying process. In fact, the low rates of processing in the last workstations of the cycle (i.e., Placing a mortar row by Foreman 2 and laying a brick row by Foreman 1 and Labor 4) nullify the previous workstation's pace and cause the entire process to slow down, generating waiting time. The last workstations work slowly because the mortar placing and bricklaying activity, in the end of each bricklaying cycle, should be done sequentially and cannot be done simultaneously. Therefore, if these two activities are carried out concurrently, the rate of processing can be enhanced noticeably, i.e., the system will operate more quickly and the labors' idle time will be reduced. To reach this improvement, it was planned to construct two walls (adjacent 4 and 6-meter wide walls) together rather than one in each process. By doing this, the rates of processing in the last workstations were raised considerably and previous activities were spontaneously sped up. To implement this method in the model, it should be modified in the way of constructing two walls concurrently.

5.4.3 Setting up the Concept of Pulling to Decrease the Labors' Waiting Time and Unnecessary Storages

Lack of materials in the working area is one of the main problems observed in the bricklaying process. As a result, labors sometimes cannot start their work because of the lack of certain materials (brick or mortar). Late delivery of these materials, in addition to wasted time, causes labors and equipment to be idle, and therefore the labor productivity and efficiency are reduced considerably. On the other hand, delivery of materials to the working area prior to demand generates unnecessary storages, which increases handling and distance to the working area. It takes the labor's time and does not add value to the final product, so that it is assumed as an NVA activity from lean approach and therefore, should be minimized, if not eliminated. Furthermore, some materials such as mortar lose their quality if they wait more too long.

The concept of pulling in the bricklaying process can be established by effective interactions between the foremen in the working area and the labors responsible for hauling materials. Consequently, the upstream workstations (such as mortar making or brick preparing workstations) conform themselves to the bricklaying and mortar placing pace in the working area, so that the unnecessary brick storages in the working area and the time interval between making and utilizing a unit of mortar are minimized. This principle was applied to the model by implementing the modules that send signals from downstream to upstream workstations.

To prove just-in-time delivery performance during the bricklaying processes, the amount of surplus bricks in working area was obtained continuously from both real world and lean model and the results are compared in Fig. 9. As can be seen, the surplus bricks in the lean model (performing two walls concurrently) are not only less than the real world models, but also are decreased to 40 bricks when construction of a wall is completed. It means that the extra hauling of materials will be reduced more than 50% in the lean bricklaying process. Table 2 also compares the average waiting time of each mortar unit between the real world models (both 4 and 6-meter wide walls) and the lean bricklaying process. It shows that the time interval between mortar making and mortar utilization, for each unit of mortar, is reduced from almost 30 to 15 minutes. As a result, the mortar quality remains acceptable. It should be noted that the data in both Fig. 9 and Table 2 were calculated based on the

Table 2. Comparison of the Average Time Interval from Making to Utilizing a unit of Mortar between the Real World and Lean Bricklaying Models

	Average time interval from making to utilizing a unit of mortar (min)	Standard Dev.
4-meter wide walls	27.12	2.40
6-meter wide walls	31.35	1.76
Lean model	15.57	1.44

average of 20 replications for the real world and lean simulated models.

Introducing the lean principles to the real world modeled to a new model, which is called the lean model and illustrated in Fig. 10.

5.5 The Lean Bricklaying Model Results

After applying the lean principles to the real world model and constructing the lean model, it is time to evaluate the potential of

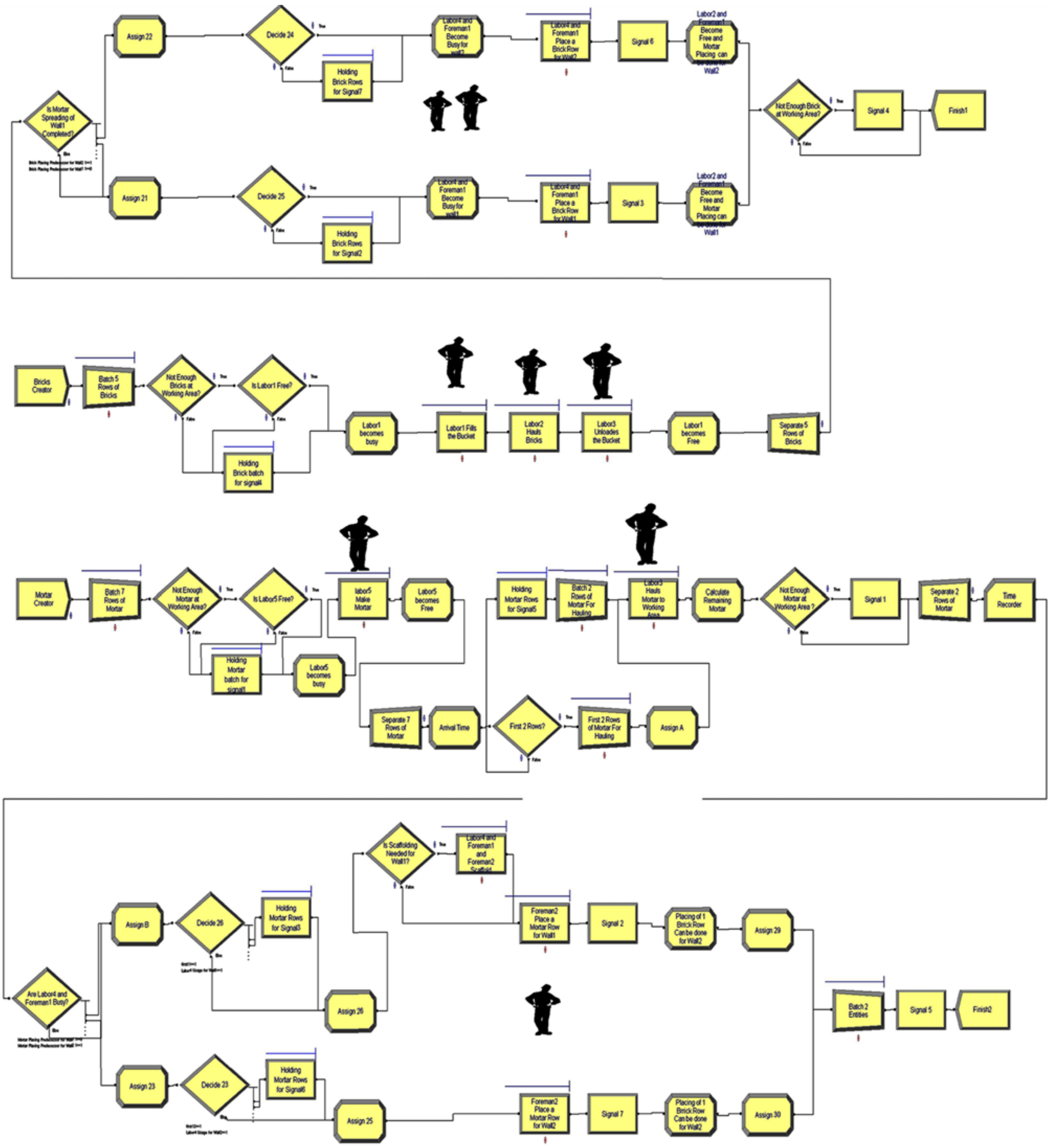

Fig. 10. Simulated Model of Lean Bricklaying Process by ARENA

Table 3. Comparison of Cycle Time, Productivity and Process Efficiency Real World and Lean Bricklaying Models

	Cycle time (min)	Labor productivity (man-hours/m^2)	Process efficiency (%)
4-meter wide walls	117.64	1.07	34
6-meter wide walls	129.01	0.79	32
Lean model	144.75	0.53	45
Improvement (%)	41*	43**	27**

Note: The quantities were calculated based on the average of 20 replications for both the real world and lean models.
*Actually, it takes 144.75 minutes for concurrent performing two walls in the lean process. Hence, the sum of the cycle times of 4 and 6-meter wide walls, i.e., 246.65 min (117.64+129.01) were used to compare with the lean model cycle time.
**The average labor productivity of 4 and 6-meter wide walls, i.e., 0.93 ((1.07+0.79)/2) were used to compare with the labor productivity in the lean model. The same procedure was done for calculation of process efficiency improvement.

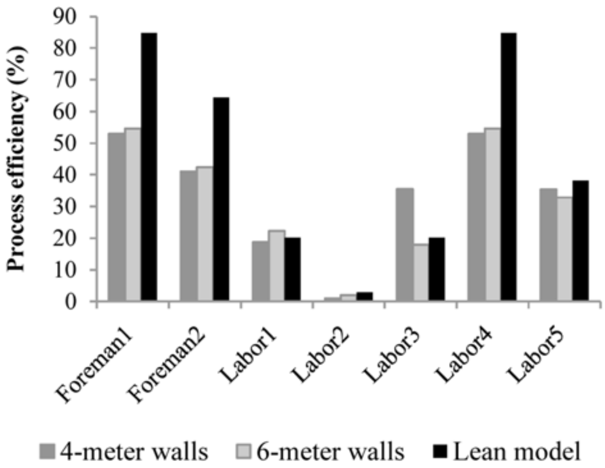

Fig. 11. Comparison of the Labors' Efficiency between the Real World and Lean Bricklaying Models

lean principles with respect to bricklaying process. By analyzing the simulation outputs for the real world and lean model, it is possible to assess the effect of implementing lean principles. To do so, *process efficiency, labor productivity and cycle time* of the real world models (both 4 and 6-meter wide walls) were calculated and compared with the lean model. The results of the comparison are summarized in Table 3.

5.5.1 Process Efficiency

Efficiency is a significant performance indicator in a process (Picard, 2000). Considering the lean approach, process efficiency can be measured by comparing the time spent on VA activities to the total cycle time (based on Al-Sudairi 2007). In fact, it can be an appropriate assessment of how effectively laborer's work. Process efficiency in this study is calculated by the ratio of laborer's time consumed on VA works to the total labor time in the bricklaying process (Eq. (1)).

$$\text{Process Efficiency} = \frac{\text{Labor time consumed by value} - \text{adding works}}{\text{Total labor time}} \quad (1)$$

As can be seen in Table 3, the process efficiency in the lean model increased to 45%. This is the result of the lean principles, which were applied to the real world model in order to achieve lean goals. In fact, these free and simple modifications led to laborers efficiency improvement, which resulted in process efficiency improvement. For more clarification, laborers' efficiency comparison (individually) between the real world models and the lean one was illustrated in Fig. 11.

5.5.2 Labor Productivity

Since flow processes are evaluated in terms of time, construction operations can be simply measured and compared in terms of productivity rates (Dunlop and Smith, 2004). Productivity in the form of "inputs/outputs" which considers only labor as an input is commonly used in the construction industry (Park, 2006), and therefore, it is used in this study. According to the nature of bricklaying process, labor performance is the main factor affects on productivity value. Therefore, the equation is:

$$\text{Labor Productivity} = \frac{\text{input}}{\text{output}} = \frac{\text{Actual Work Hours}}{\text{Installed Quantity}} \quad (2)$$

As shown in the above equation, labor productivity is measured in actual work hours per installed quantity; that is, the number of work hours required for performing a square meter of wall. When the productivity is defined in this form, it should be mentioned that a lower productivity value indicates a better performance.

Results of the real world and lean bricklaying model were used in order to calculate and compare their labor productivity. As listed in Table 3, the productivity of the real world bricklaying process is 0.93 man-hours/m^2, which is the average labor productivity of 4 and 6-meter wide walls. It means that each square meter of the walls takes averagely 8 minutes to perform, while there are seven labors worked in the bricklaying task. These amounts reduce to 0.53 (man-hours/m^2) and almost 5 (minutes) in the lean bricklaying process. Effective coordination between upstream and downstream workstations, more efficient use of labor's time and focusing on the transferred value are the main factors that improve the labor productivity.

5.5.3 Cycle Time

On time completion of construction processes not only leads to on time completion of a project, but also can improve labor productivity and process efficiency. Therefore, cycle time comparison of construction process alternatives can be an appropriate evaluation.

More value generation, through lean principle application, made the bricklaying process faster. The process efficiency comparison proves that the labors spend more time (27% more) on VA works. In fact, the nature of lean process persuades labors to do more VA works instead of waiting or doing NVA activities, so that the process is completed sooner. As can be seen in Table 3, it takes almost 145 minutes to construct two adjacent walls in the lean model, while in conventional practice, it took 246 minutes. Therefore, the cycle time improved more than 40%. Needless to say, the cycle time reduction, directly, leads to the total project time to be decreased. As a result, the project is completed in a month rather than 50 days.

6. Conclusions

This paper aimed at presenting a systematic approach of applying lean production principles into a given construction process, bricklaying process, at a construction job site using a computer simulation software, *ARENA*. This study shows that such principles can play a significant role in improving the construction processes.

Preliminary results of the simulation show more than 70% share of non value-adding works in the original bricklaying process (including non value adding activities and waiting time), which was a good reason for implementing lean principles. Applying three main lean principles including “implementing flow view of production”, “generating value”, and “Setting up the concept of pulling” to the original bricklaying process leads to 41% reduction in cycle time, 43% improvement in labor productivity and 27% enhancement in process efficiency.

Applying lean principles into various processes with different features can lead to different results. Therefore, it requires a comprehensive investigation to choose the most effective lean principles for application. Furthermore, as can be seen in this paper, in order to implement lean principles, the processes required to be modified or altered in some way. The probable costs of these modifications are acknowledged by the authors. However, in the studied bricklaying case, the modifications toward being lean are not only costly, but also beneficial and lead to the remarkable performance improvement.

Finally, it should be concluded that although this study is conducted for only one construction operation, it can be predicted that all of construction processes can potentially be optimized through the application of lean principles, which will lead to an effective promotion in the construction industry.

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Appendix

Table 4. Basic Operation Process Chart (OPC) (used in process mapping)

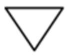
Symbol	Title	Description
	Operation	A complex action or process (possibly described elsewhere), often changing something.
	Transport	Movement of people or things. May be accompanied by a distance measurement.
	Delay	Idle time of people or machines, or temporary storage of materials.
	Storage	Permanent storage of materials or other items.
	Inspection	Checking of items to ensure correct quality or quantity.

Table 5. A Brief Description of ARENA Modules

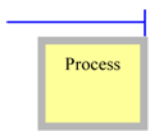
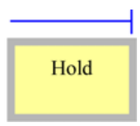
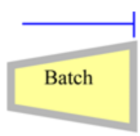
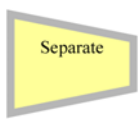
Module Name	Module Symbol	Description
Creator		This module is intended as the starting point for entities in a simulation model. Entities are created using a schedule or based on a time between arrivals
Assign		This module is used for assigning new values to variables, entity attributes, entity types, entity pictures, or other system variables
Decision		This module allows for decision-making processes in the system. It includes options to make decisions based on one or more conditions (e.g., if entity type is Gold Card) or based on one or more probabilities (e.g., 75% true; 25% false).
Process		This module is intended as the main processing method in the simulation. Options for seizing and releasing resource constraints are available. The process time is allocated to the entity and may be considered to be value added, non-value added, transfer, wait or other.
Hold		This module will hold an entity in a queue to either wait for a signal, wait for a specified condition to become true (scan) or be held infinitely (to later be removed with the Remove module).
Batch		This module is intended as the grouping mechanism within the simulation model. Batches of entities can be permanently or temporarily grouped. Temporary batches must later be split using the Separate module.
Separate		This module can be used to either copy an incoming entity into multiple entities or to split a previously batched entity

Table 5. (Continued)

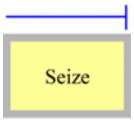
Module Name	Module Symbol	Description
Delay		The Delay module delays an entity by a specified amount of time.
Seize		This module allocates units of one or more resources to an entity. The Seize module may be used to seize units of a particular resource
Release		The Release module is used to release units of a resource that an entity previously has seized.
Signal		The Signal module sends a signal value to each Hold module in the model set to Wait for Signal and releases the maximum specified number of entities

Table 6. Process Distribution Parameters of the Bricklaying Activities (used in simulation model)

Activity	Material quantities processed	Distribution Fitted	Parameters of Fitted Distribution
(4-meter width walls)			
Labor1 Fills the Bucket	5 Rows of bricks	Weibull	α=14.70 β=5.69
Labor3 Unloads the Bucket	5 Rows of bricks	Normal	σ=0.52 μ=7.31
Labor4 and Foreman1 Place a Brick Row	1 Row of bricks	Normal	σ=0.42 μ=3.65
Labor3Hauls Mortar to Working Area	2 Rows of Mortar	Normal	σ=0.21 μ=1.27
Foreman2 Place a Mortar Row	A Row of Mortar	Johnson SB	γ=-0.086 δ=1.14 λ=1.72 ξ=1.77
(6-meter width walls)			
Labor1 Fills the Bucket	5 Rows of bricks	Uniform	α=4.83 β=6.67
Labor3 Unloads the Bucket	5 Rows of bricks	Lognormal	σ=0.07 μ=2.07
Labor4 and Foreman1 Place a Brick Row	1 Row of bricks	Normal	σ=0.50 μ=4.27
Labor3 Moves Mortar to Working Area	2 Rows of Mortar	Uniform	α=1.02 β=1.64
Foreman2 Place a Mortar Row	1 Row of Mortar	Johnson SB	γ=-0.02 δ=1.34 λ=2.27 ξ=1.95
(Common Activities in both walls)			
Labor2 Hauls Bricks	5 Rows of bricks	Lognormal	σ=0.11 μ=0.021
labor5 Makes Mortar	7 Rows of Mortar	Triangular	μ=14.5 α=10.99 β=16.24
Labor4, Foreman1 and Foreman2 Scaffold	---	Normal	σ=1.31 μ=11.34