Proceedings of the 2010 Winter Simulation Conference
B. Johansson, S. Jain, J. Montoya-Torres, J. Hugan, and E. Yücesan, eds.

ADVANCED SIMULATION OF TOWER CRANE OPERATION UTILIZING SYSTEM DYNAMICS MODELING AND LEAN PRINCIPLES

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ABSTRACT

Tower cranes are one of the major equipments used in the construction of high-rise buildings. Simulation is an effective tool in modeling complex construction operations such as tower crane lifting. Lean principles combined with a simulation module can significantly reduce the cost and improve time management of construction. This paper presents an integrated system dynamics model with Lean concepts to simulate tower crane operations. This paper also presents a new type of tower crane with the following innovative futures: 1) two jibs; 2) propellers to swing the crane; and 3) wireless video monitoring technology. This double-jib crane will potentiality improve the productivity of the crane operation. A case example is presented and the results of the model are used to illustrate the advantages of utilizing a double-jib crane in the construction process. The results indicate that advance simulation techniques can minimize the resource requirements of crane operation.

1 INTRODUCTION

A typical high-rise building construction project involves lifting objects of different sizes and weights. Prefabrication, preassembly, and modularization are employed in construction projects to facilitate the relocation of portions of work into offsite fabrication centers. However, this relocation of work implies much more frequent crane use. Cranes are involved in many different tasks and are the most shared resources on construction sites. At present, planning for tower crane operations is mostly is performed intuitively and based on experience. Knowledge-based expert systems have been applied to construction operations for several years, although primarily for the purposes of equipment selection, site layout optimization (Lim et al. 2005; Chung 1999; Alkass, Aronian and Moselhi 1993), and scheduling of construction activities (Shaked and Warszawski 1992; Alshawi and Jagger 1991; Moselhi and Nicholas 1990). Today, however, lift planning and optimizing crane activities are receiving considerable attention from practitioners and academics to ensure safety and economy within the workplace. Efficient utilization of tower cranes greatly depends on skilled judgments that account for a number of technical, schedule, and financial factors. As the number of work tasks and the demand for tower cranes increases, planners may be required to make decisions on job conditions for a particular situation. A poor decision is likely to have significant negative effects, which will lead to additional costs and possible delays. The construction industry is seeking new innovative approaches to optimize its resources including tower cranes.

Current research in the domain of tower crane simulation focuses primarily on developing tools to assist practitioners in the crane scheduling process. Leung and Tam (2003) demonstrated that simulation can be used to improve the scheduling strategies and reviewing the floor construction schedule. Appleton et al. (2002) developed a special purpose simulation model using priority rating logic. Shi and AbouRizk (1997) presented a resource-based modeling method for construction simulation. Shi (1999), for instance, developed a simulation method based on construction activity. A basic 4D Computer Aided Design (CAD) simulation model allows users to visualize the expected evolution of building structures during a given period of construction based on the schedule of activities. 3D visualization is helpful in the verification and validation of crane operations. Al-Hussein et al. (2006) presented a methodology for integrating 3D visualization with special purpose simulation for tower crane operation. All these simulation models are helpful in better understanding construction operation. However, the researchers didn't consider the continuous flow in these simulation models. To introduce continuous flow in crane operation, Lean principles can be applied. Lean principles can improve tower crane operation performance along with the quality of work. However, before application of Lean, the problem within the simulation model needs to be identified. System dynamics modeling is an efficient tool to address such a problem.

This study develops a methodology to create an advanced simulation model of tower crane operation utilizing system dynamics modeling and Lean principles. An innovative tower crane with two jibs (GG Crane Group 2010) is considered as one of the options to improve crane operation. A case study is performed with details to illustrate the effectiveness of the proposed methodology.

2 METHODOLOGY

Figure 1 illustrates the process used in the proposed tower crane simulation model. A case study-based approach is utilized to demonstrate the proposed methodology. In practice, a tower crane is selected based on the maximum load needed to be lifted, size of the load, site layout, and the reach or capacity. In the construction planning stage, a particular configuration of the tower crane is chosen to yield the required heights, reach, and capacities. Tower crane operation can be broken down into separate activities and the number of crane requirements depends on: (1) source location; (2) destination location; (3) weight and size; (4) priority setting; (5) possible location of crane; (6) jib length; (7) rotating speed; and (8) reach. To simulate the lifting operation, travel speeds for hoisting, radial, and horizontal trolley movements also need to be considered. After selecting the number of cranes, the percentage of utilization of each tower crane is then calculated. The simulation model keeps searching for the utilization of each crane that exceeds 90%.

To identify the problem in the simulation model a system dynamics model needs to develop. A system dynamics model is built to understand a system of forces that have created a "problem" and continue to sustain it. Developing a model of a system or process without specifying how the system needs to be improved or what specific behavior is problematic is difficult. The goal of the model is to address the problem in that system. After choosing the problem area that needs to be focused on, an improvement method needs to be integrated with the system. In this paper two different concepts have been proposed to improve the utilization of tower cranes: (1) using a two-jib tower crane instead of or alongside a single-jib tower crane when required, and (2) application of Lean principles to minimize process waste and increase work flow.

3 BACKGROUND AND DESCRIPTION OF THE TOWER CRANE WITH TWO JIBS

In 1968 Belgium, Mr. Gaspard Gillis, founder of GG Crane (GG Crane Group 2010), designed, patented, and built cranes with two jibs, which he operated for personal use in the 60s and 70s. After 40 years, Mr. Patrick Gillis, son of Mr. Gaspard Gillis, decided to redesign the GG crane and bring it to the international market. This crane consists of a central tower with two jibs placed at both sides of the tower as shown in Figure 2. These two jibs are rotated around the central tower by propellers mounted at the end of each jib. This technique eliminates the torque forces generated in the swinging desk of the tower section (mast) of the crane. These innovations, the double jib and using propellers at each end to swing the crane, allow for the increase of both reach and capacity of the tower crane. A video monitoring system to control the hooking operation has been added to the crane through a wireless video camera installed on the trolley of each jib. The crane operator can view the lifted material in real time utilizing the wireless video monitoring system which can significantly improve the safety and productivity of the lift operation. The jib lengths of the GG crane are larger than conventional cranes and vary from 120m (2 x 60m) to a total of 300m (2 x 150m).

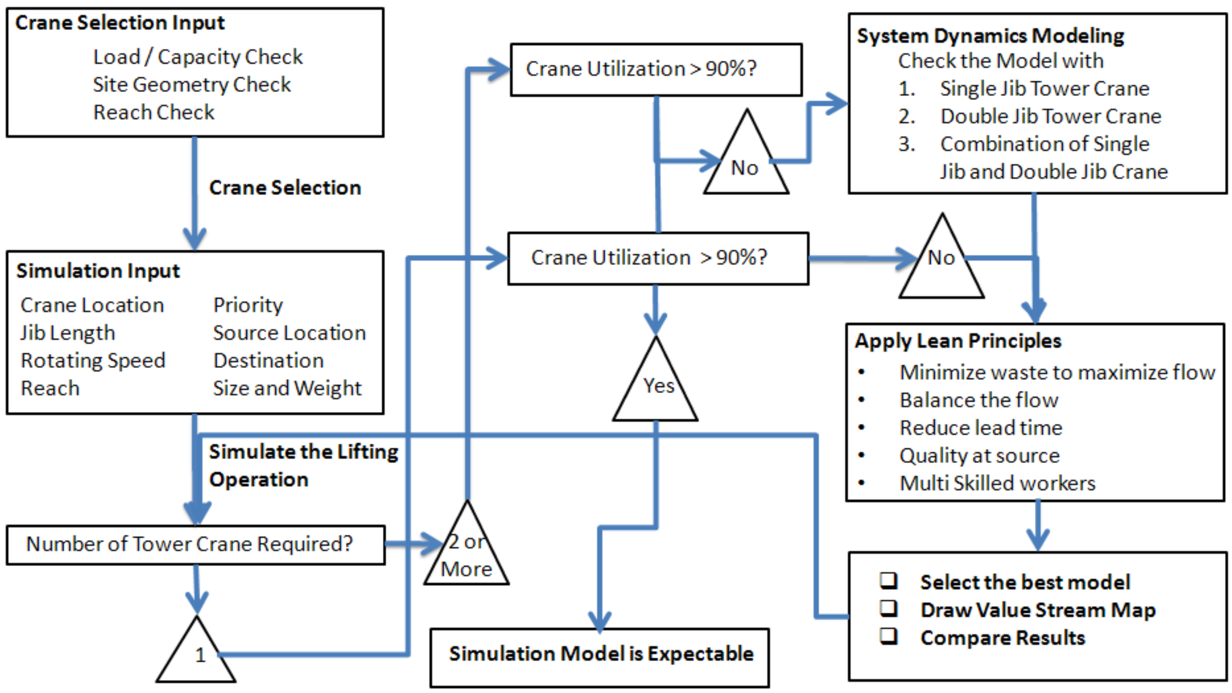


Figure 1: Flow Chart of the Simulation Model

Figure 2: Tower Crane with Two Jibs

4 LEAN PRINCIPLES

Lean Production was introduced by Toyota Manufacturing Corporation after the Second World War and Lean theory has been used by the manufacturing company for several years. The goal of Lean is to provide products or services to customers with the highest quality, at the lowest cost, and in the shortest time by eliminating waste. The basic five principles of Lean are (1) specifying value from the customer's perspective, (2) drawing all the steps across the production value stream, (3) making the value creating steps flow without waste, (4) creating pull at the request of the customer, and (5) seeking perfection. Many researchers have transferred Lean theory from manufacturing to the construction industry. Lean concepts have been proposed for the lifting process at the early stage of planning when tower crane simulation is carried out.

5 CASE STUDY

The proposed methodology has been tested in the case of a pre-cast residential building. This building was a 28,000m^2, high-rise building consisting of 9 floors, two underground and seven above ground. The building footprint was 60m x 80m, and the total number of pre-cast units required to construct this building was 5,800. The general contractor decided to use tower cranes for transporting these pre-cast units from site inventory to the installation location. To meet the project schedule, a minimum of 30 pre-cast units had to be installed per day and need to complete the installation by 190 working days. The construction site had limited storage capacity for these large pre-cast units. Thus, the least number possible would be stored on site. Other activities, such as (1) unloading and inspecting pre-cast units and storing them in the onsite inventory; and (2) installing the unit after hooking operation, needs to be simulated. The solution required selecting the most efficient feasible tower crane operation.

Step 1: Simulation of Crane Operation

This step was carried out to select the type and the number of tower cranes required to perform the lifting operation. Considering the geometric and lifting load constraints and following the methodology provided by Al-Hussein et al. (2006), it was found that two 60m single-jib tower cranes were required, as the building footprint was (60m x 80m) and there was no single-jib tower crane that could reach 80m available on the market.

The total available production time was 9 hours per day with a 30min lunch break and two 15min breaks. Therefore, the available production time was = 9 * 60 – 30 – 2*15 = 480 minutes per day.

Based on the simulation results, a value stream map was drawn as shown in Figure 3. From the simulation results it was found that utilizing two tower cranes with a 60m-jib length would install 33 pre-cast units per day satisfying the schedule requirement. However, an advanced simulation was carried out to check if this operation could be completed with fewer resources to minimize the cost while satisfying the schedule requirement.

Step 2: Advanced Simulation

In order to determine the ability and percentage of utilization of each process, the working time and idle time of each process were calculated as shown in Table 1.

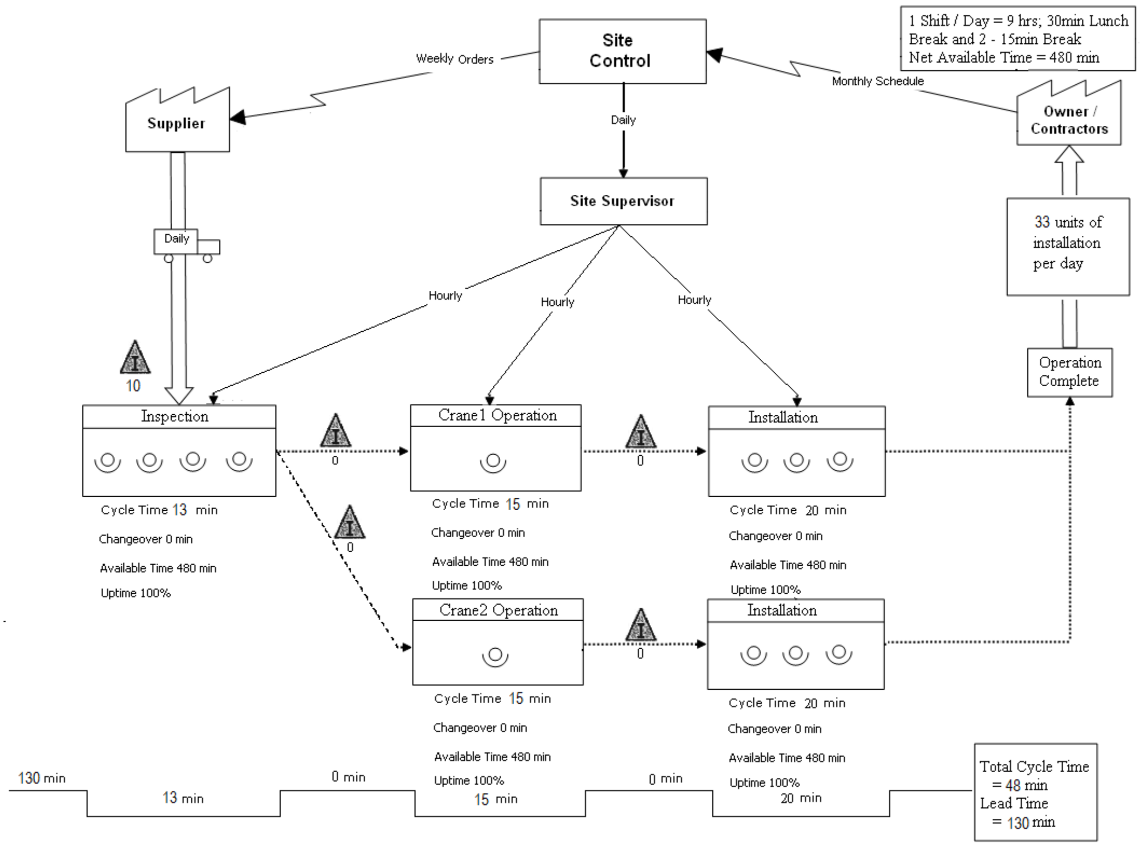


Figure 3: Design Stage Value Stream Map

Table 1: Calculation of percentage of crane utilization

Process Name	Available time (min)	Cycle time (min)	Active (min)	Idle (min)	% of Utili-zation
Inspection	480	13	429	51	89.38%
Crane 1	480	15	255	225	53.13%
Crane 2	480	15	240	240	50.00%
Installation L1	480	20	340	140	70.83%
Installation L2	480	20	320	160	66.67%

Based on the information in Table 1, it was found that the maximum utilization of a tower crane was only 53.13%. Thus, to identify the problem and to improve the simulation model a system dynamics model was developed as shown in Figure 4. The model was developed using Vensim PLE software (Vensim 2010).

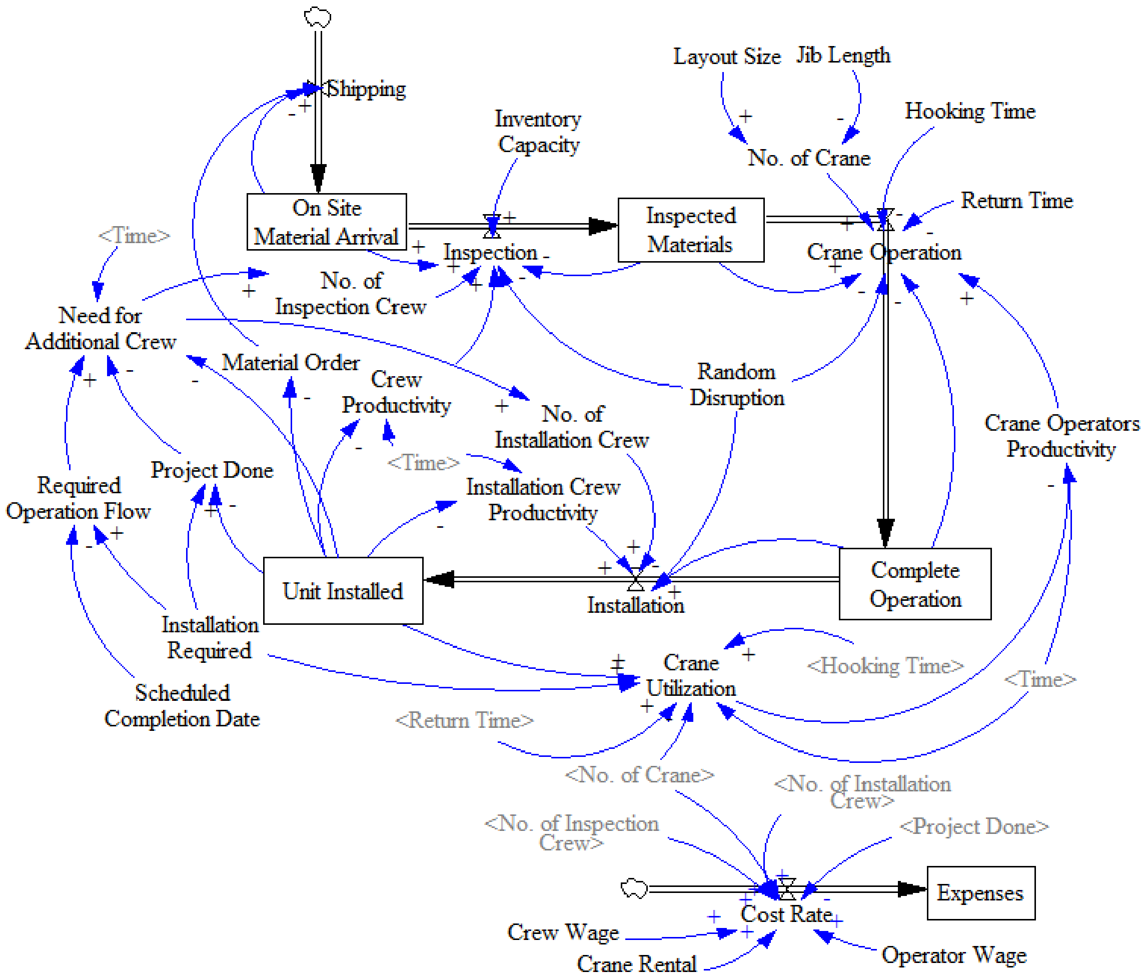
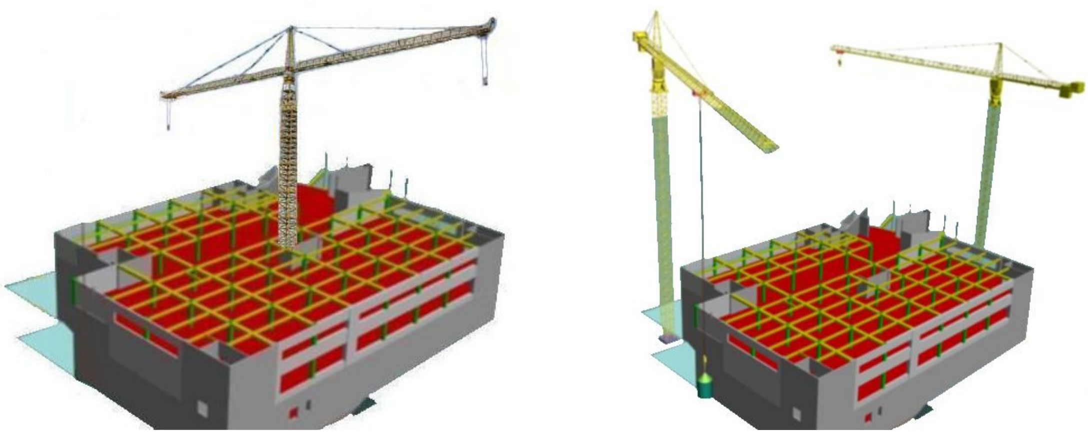


Figure 4: System Dynamics Model

The process feedback of the model (see Figure 4) was analyzed using stock and flow diagram. Shipment of the pre-cast unit depends on the material order and schedule. Generally if the order increases, the shipment needs to be increased. The number of crew available for the inspection, the productivity of the crew and shipment of the pre-cast unit (onsite inventory) positively affect on the inspection of the units. Again, disruptions due to availability of the tools or weather conditions can negatively affect the inspection process. Crane operation depends on the number of crane available, hooking time to pick and place a unit to its required position, return time of jib to pick another unit and the productivity of the crane operator. Increase of crane number increases the number of unit movements through the crane operation. On the other hand increasing of hooking time or return time decreases the number of unit movements per day. The number of crew available for the installation, the productivity of the crew and movement operation positively affect on the installation process of the pre-cast units. Based on the unit installation per day, the materials are needed to be ordered. Again increasing unit installation per day may decrease the productivity of the crew due to continuous work or tiredness. Crane utilization can be analyzed using the unit installation per day and the crane operation time. Increasing the crane utilization may also decrease the productivity of the crane operator, and decreasing the productivity can reduce the crane operation as well as reduces the number of unit installation. This feedback loop is a balancing loop. Again, the required operation flow can be calculated using the scheduled duration and number of installation required to complete the project. If the current operation flow is less than the required operation flow then additional crew is needed to recover the flow. Thus requirement for additional crew increases the number of crew for inspection process and installation process. Some random disruptions are considered in the dynamics model to analyze the process with the affect of some unexpected events such as adverse weather conditions, breakdown or absenteeism. These disruptions can slow down the operation process. Again, the developed model can calculate the total expenses based on the resources used per day and their rental cost or wages per day.

Two simulation behaviors were considered to verify the effectiveness of the proposed methodology. The first simulation considered a double-jib tower crane (GG Crane with jib length of 85 m each) as shown in Figure 5-a. The second simulation considered two single-jib tower cranes with jib length of 60 m (see Figure 5-b). The simulations were carried out to find the best option in the proper utilization of all the resources and complete the project on time.



(a) (b)

Figure 5: (a) 2 Single-jib Tower Cranes with 60m Jibs; (b) 1 Double-jib Tower Crane with 85m Jib

It was assumed that hooking time for the single-jib tower crane operation was 12 to 15min based on the complexity of the lifting material (pre-cast unit) and the source and destination location of the unit. In the simulation model, random hooking time ranging from 12 to 15 min is considered over the working hour of a day. Using the double-jib tower crane the hooking time can be reduced by 10 to 15% due to the increase of the rotating speed from using propellers positioned at the end of each jib and working with both jibs. The rental cost for a double jib crane (85m jib length) is considered 1.5 times greater than the rental cost of a single jib crane (60m jib length).

Step 3: Compare Results

By applying Lean concepts such as 5S, standard work, two single jib crane can complete the 5800 unit installation process in 174 days, where one double jib crane (GG Crane) can complete in 180 days (see Figure 6-a). One double jib tower crane operation is less expensive than two single jib crane operations as shown in Figure 6-b. Thus, utilizing two single jib cranes can complete the project 6 working days early; however, will cost \$120k more than utilizing one double jib crane. Two single jib cranes operation does not need any additional resources as it initially utilizes two cranes with operators and ten crews (4 crews for inspection and 6 crews for installation). On the other hand, one double jib crane operation is required additional crews during 90th to 130th working days as shown in Figure 6-c (1 means additional crew required) to recover the schedule pressure. The utilization of crane for two single jib cranes operation is around 50% where for one double jib crane operation the crane utilization is around 90% (see Figure 6-d). The resource utilization between the two simulation options is presented in the Table 2.

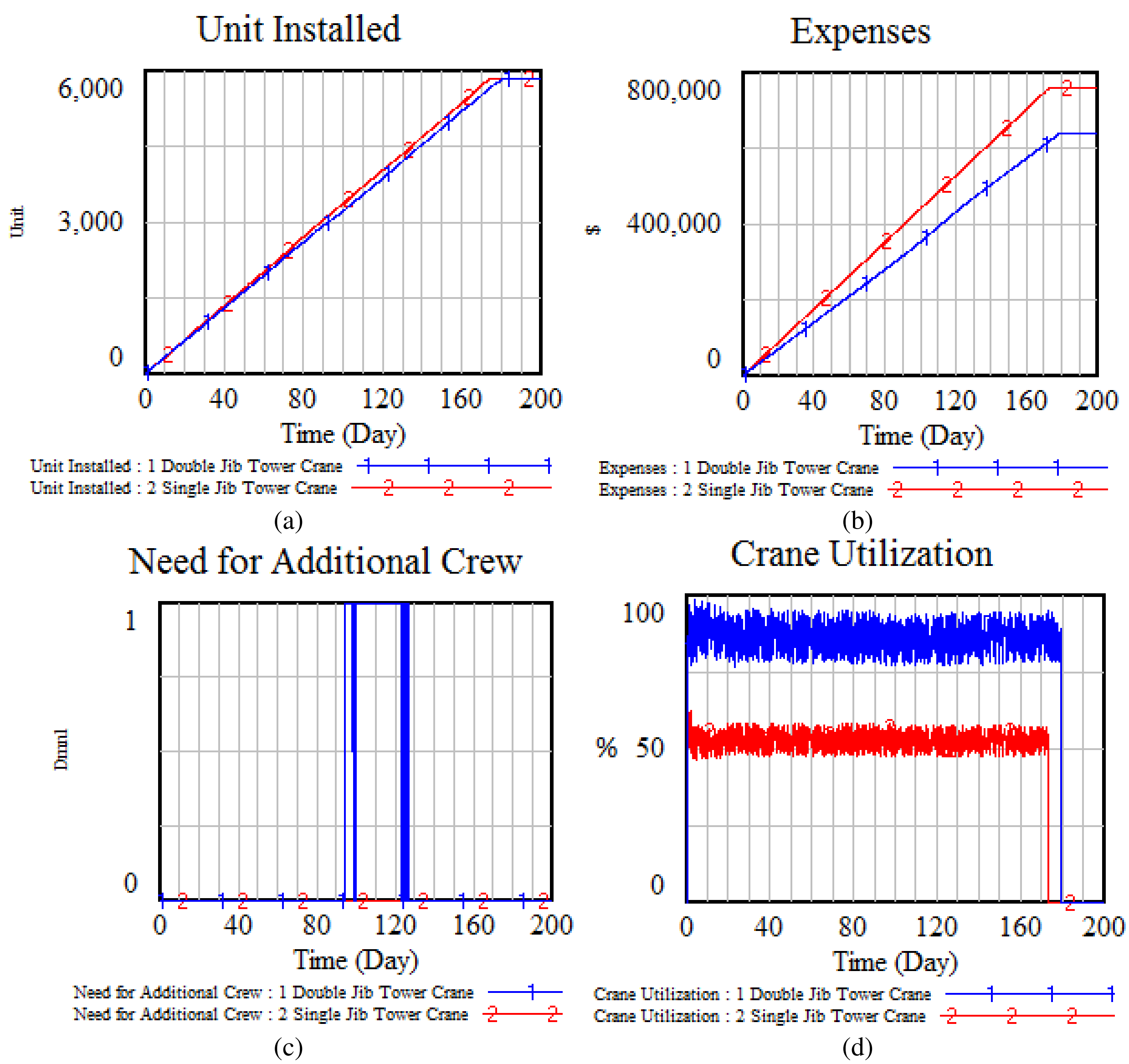


Figure 6: (a) Unit Installation vs. Time; (b) Expenses vs. Time; (c) Additional Crew Requirements over Time; and (d) Utilization of Crane over Time

Table 2: Resource utilization between the two simulation options

Variables	**2 Single-Jib Tower Cranes**	**1 Double-Jib Tower Crane**
No. of Cranes	2	1
Average Crane Utilization	50%	90%
No. of Crane Operators	2	1
No. of Crew	10	9 (Day 1 to 92 and 127 to 180) 11 (Day 93 to 128)

From Table 2 and the design results it is found that one double jib tower crane operation required less resources and less expensive while satisfying the project schedule than two single jib cranes operation. Thus the best possible design solution for this case study is to utilize a double jib crane with 85 m jib length to simulate the lifting operation.

6 CONCLUSIONS

This paper presents the application of system dynamics modeling and Lean concepts in simulating the operation of tower cranes. This paper also evaluates the potential use of two jibs tower crane in construction industry. A pre-cast building construction process is modeled and simulated with the proposed methodology. The output of the basic crane simulation model indicates that it satisfies the project schedule; however, it does not optimize the resources used in the lifting process. Lean principles and utilizing a two-jib tower crane can minimize the resource requirement and significantly reduce the cost of construction. This research has been motivated by the large number of tower cranes used in the construction industry, and the consequent need to improve productivity and safety. A two-jib tower crane with wireless video monitoring technology can significantly improve the productivity and safety of the tower crane operation. A system dynamics model of tower crane operations is developed to illustrate the powerful future and capabilities of the new innovative tower crane with two jibs.

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