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Article

Effective Crew Allocation Using Discrete-Event Simulation: Building Scaffolding Case Study in Thailand

Nathee Athigakunagorn[a] **and Charinee Limsawasd**[b,*]

Department of Civil Engineering, Faculty of Engineering at Kamphaeng Saen, Kasetsart University, Nakhon Pathom, 73140, Thailand
E-mail: [a]nathee.a@ku.th, [b]charinee.l@ku.th (Corresponding author)

Abstract. A paradigm was developed to illustrate the performance and capabilities of discrete-event simulation (DES) in dealing with the complexity and uncertainty of construction processes. EZStrobe (a promising DES tool) was utilized due to its simplicity and the moderate effort required. A case study investigated the scaffolding installation process for a high-rise building project in Thailand. The activity cycle diagrams (ACDs) were constructed accordingly to represent the complex construction processes and associated activities of the case study. Data analyses were performed to propose an effective strategy that contributed substantially to productivity improvement. The results showed that for five workers, the ratio of installers to delivery workers to lower-level workers of 1:1:3 produced the lowest total idle time. Nevertheless, doubling the numbers of workers produced the shortest total construction duration but with higher idle time and construction labor cost. The crew fleet was effectively allocated depending on two main attributes: (1) proportion between installers and delivery workers; and (2) number of lower-level workers. The findings from this study can further direct project planners to achieve proficient onsite resource arrangements, especially under time and cost constraints.

Keywords: Resource allocation, discrete-event simulation, scaffolding, building project.

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1. Introduction

As a construction project increasingly involves very complex processes [1-2], an effective modelling technique is necessary to analyze the complicated, interactive and dynamic nature of construction. Moreover, a superior technique is required so that problem solving can be performed without disrupting the ongoing construction processes. Evidence [3-4] has been presented on the successful implementation of computer-based modelling and simulation in analyzing construction operations over the past decades. Several studies have enumerated applications and the advantages of using computer modelling and simulation tools in construction [5-11].

Besides complexity, construction projects always encounter uncertainty that inevitably occurs during operations. This uncertainty can cause poor performance, which results in overruns of construction costs and project delays [12]. Many factors have been mentioned that can cause uncertainty and impact on construction projects, such as the weather, labor supply, revisions, reworking, productivity, waiting time delays, and poor project management [13-16]. In order to address the challenges of complexity and uncertainty, discrete-event simulation or DES has been recognized as a promising computer-based modelling technique with its capability of handling complex construction conditions by adapting a computer-based method to model an electronic realistic prototype that represents a real operational system [17].

In construction work, temporary structures are important elements that deserve substantial attention due to their impacts on the construction schedule and indirect construction costs [18-19]. An Occupational Safety and Health Administration (OSHA) report showed that 65% of construction workers are routinely associated to the scaffolding task [20]. Furthermore, there are claims that improper planning of scaffolding systems has a huge impact on construction expenditure. Apart from the safety issue, several studies have acknowledged the considerable effect of the labor-intensive nature of scaffolding on construction cost and time [19, 21-22]. The scaffolding component can also involve a critical decrease in work productivity as a result of idle time, reworking and excessive delivery time [23]. However, most temporary scaffolding systems are given less importance and lack effective resource planning and management nowadays [19, 21]. As such, there is a pressing need for a proficient technique that contributes to effective resource allocation and planning management to promote productivity improvement in scaffolding systems.

Due to the aforementioned research gaps and challenges, DES was adopted in this study to demonstrate its capabilities and application in analyzing and modelling the complexity and determining the uncertainty of the scaffolding installation task of a building construction project in Thailand. The results from this study are expected to help contractors and construction managers to analyze a complex construction project and further improve construction processes, facilitate resource allocation, and enhance the work productivity. The proposed paradigm can be utilized as a decision-support tool for managing crew allocation and configuration of the scaffolding process and other construction processes. The rest of the paper is organized as follows. The next section describes data collection, and basic knowledge of the scaffolding components and installation. Then, explanations of model development, input data and analysis assumptions are provided in the model construction section. After that, the analyses present the performance and capabilities of the developed DES model in facilitating effective resource allocation in the results and discussion. This is followed by the conclusion.

2. Data Collection

2.1. Data Sources and Scopes

This study aimed to investigate the performance of DES in improving the work productivity of a building construction project. Therefore, the scaffolding installation process was selected for analysis because it is repetitive, labor-intensive, and hard to effectively allocate proper crew configuration. A substantial impact on productivity improvement can be expected based on an effective recommendation on resource allocation. The scaffolding installation activities of one high-rise condominium building in Thailand were collected using video recording in this study. Information and data were subsequently extracted to determine the amount of work performed, the work sequence, activity duration, and activity resources in terms of crew workers and scaffolding components. Explanations of the data collection process for each essential input parameter are provided below:

<u>Amount of performed work</u> was calculated as total number of scaffolding components for the entire building installation, which was based on the whole building area measured in square meters (m^2) and the installing area per one bay.

<u>Work sequence</u> was initially collected at the construction site by interviewing the contractor's project engineer. In addition, site investigations were performed over a period to observe common practice and the continuity of sequences in the repetitive scaffolding installation process.

<u>Activity duration</u> was determined and extracted from the recorded video simultaneously with the work sequence. Each activity in the work process was originally identified by start and end points, which corresponded to the activity duration measurement. Sufficient rounds of recording were repeated to collect several samples for the duration of an activity and this information was further used to formulate the distribution pattern to represent the uncertainty inherent in the construction.

<u>Activity resources</u> were gathered by observing the type and number of workers needed for installing each bay of scaffold. In addition, the number of scaffolding components was determined based on the amount of performed work initially calculated.

All these data were later used to construct the ACD to depict the systematic network of a complex construction process showing activities, resources, and interactions. In this paper, the different types of activities were represented in forms of the Normal and Combi, which are basic elements in ACD and were linked in order according to the work sequence. The number of scaffolding components that needed to be completed and the number of workers were incorporated into the ACD in the form of the Queue (another basic ACD element) with the number of associated resources appearing in the determined Queue node. The relationships of construction activities were also defined as links or interactions between the basic ACD elements. The activity durations were then added into the related Normal or Combi forms. Duration can be presented either in terms of a deterministic or probabilistic format. However, the probabilistic duration of an activity requires repetitive data collection to represent the time variations in terms of activity duration distribution. The associated instructions and rules for the ACD development and analysis can be further referenced from the original articles [24-25].

2.2. Scaffolding Components and Installation Process

The type of scaffold in the case study was a ring-lock scaffolding system. It is widely used in the industry due to its low cost, simplicity to install, and adaptability to different functional areas. This system is the most modern and versatile among all scaffolding mechanisms available in the industry, providing high flexibility and stability of structure with good load-bearing strength. Furthermore, it requires installation components for the scaffolding system to be easy to assemble and store, with the minimal effort and time required. Figure 1 illustrates the basic scaffolding elements in this paper.

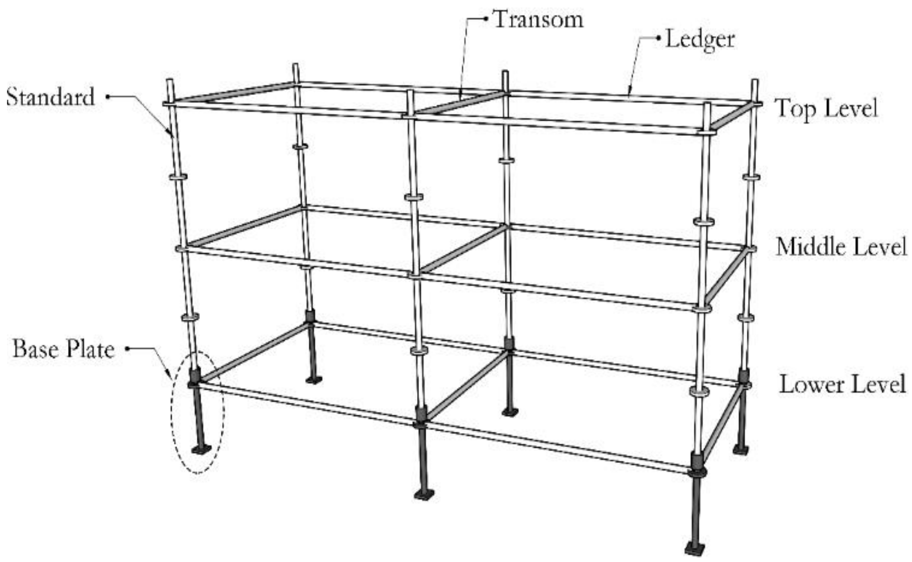

Fig. 1. Scaffolding elements.

The structural system is composed of four basic elements: standards, ledgers, transoms, and base plates. A standard is a vertical structure connecting the scaffolding system directly to the ground. The lower part of the standard is attached into a base plate to disseminate the load of the scaffold. A ledger is a horizontal structure running between standards in the long direction to provide support and distribute the weight of the structure. An assembled standard is also supported by a transom that is placed over ledgers.

The process of each bay starts from a worker taking two base plates from the pile of material and carrying them to a designated location. The worker then returns to the pile to get one of the two ledgers needed for the installation of the lower level. Next, the lower-level ledgers are connected to the base plates using couplers. The worker will go to the pile again to get transoms which are then placed over and attached to the ledgers. Standards are next securely adhered to the base plates. After that, the middle-level ledgers and the transoms are connected to the standards with couplers. The process lastly involves the worker climbing over the middle level to install the ledgers and transoms at the top level of the scaffold. This is repeated for all bays installed at the construction site. In practice, a worker can carry two base plates at a time, whereas the other members of the scaffold structure can be carried one piece at a time.

3. Model Construction

3.1. Discrete-Event Simulation (DES)

DES is a modelling technique that is superior in codifying dynamic and complex behaviors of a real or imaginary system. The simulation can be executed on the platform of either general programing languages or simulation-specific tools [26]. Several research studies have claimed its effectiveness in handling the nature and characteristics of a construction project. Until now, a large number of DES tools (e.g. CYCLONE, COOPS, Stroboscope, and EZStrobe) have been introduced to facilitate the analysis and visualization of a complex problem [26-28].

As DES has been widely recognized in construction-oriented research, it has been adopted to address many aspects in construction projects. For example, [5], [6], and [11] used DES in evaluating the environmental impacts due to construction activities. In addition, [3] and [15] demonstrated an application of DES in planning construction processes that depend greatly on the utilization of heavy equipment fleets. The other applications exemplified productivity analysis for precast-concrete, hollow-core slab installation, road structure construction and cement loading process [30-32].

3.2. Activity Cycle Diagram

The case study was modelled using a promising DES tool, namely EZStrobe, to satisfy the objective of simplicity with moderate effort required for operations. This paper constructed the ACDs of the scaffolding installation process by separating it into six main parts, as shown in Figs. 2 to 7, according to the information gathered at the construction site as described in the previous section. The first part of the model was established to present the process of installing base plates at the four corners of the specified bay. One set of scaffold was composed of four base plates, four standards, six transoms and six ledgers. However, for the next set, only two base plates, two standards, three transoms and three ledgers were required to complete the process because they had to connect with the existing structure and, hence, shared some members, as shown in Fig. 1. The ACD assumed that the leftmost panel in Fig. 1 (i.e., two base plates, two standards, three transoms) had already been installed. This means the same number of members were required for all sets, which reduced any unnecessary complexity in the ACD. Moreover, a ledger and transom were aggregated here as a longitudinal structure for model simplicity and are henceforth called a 'ledger' in the ACD.

The process proceeds from the material delivery at "Get_BasePlate" when there are sufficient amounts of materials, workers and allowable working space at "BasePlate", "Worker", and "BP_CanInstll", respectively, before the installation of the base plate at "Install_BsPlt". The number on the arrows between these activities identifies the number of resources that are needed so that the activity "Get_BasePlate" can start. For example, the activity requires one worker, two base plates and three resources from "BP_CanInstll" Queue (discussed later in this section). If these required resources are not adequately available at the same time, the immediately succeeding activity will not be initiated.

Then, two actions are concurrently performed, as the worker returns under "Return_BsPlt" to begin the next delivery round while the resource instances of allowable working laps (i.e., the allowable spaces to install the lower-level ledger) are added through "LL_CanInstll" to trigger the next process. Once two base plates have been installed, the worker can connect three ledgers to four base plates (two base plates from the previous round and two base plates that have just been installed), which is indicated by number "3" on the link between "Intall_BsPlt" and "LL_CanInstll". The total number of installed base plates is then stored in "BsPlt_Installed". Figure 2 demonstrates the ACD for the base plate installation.

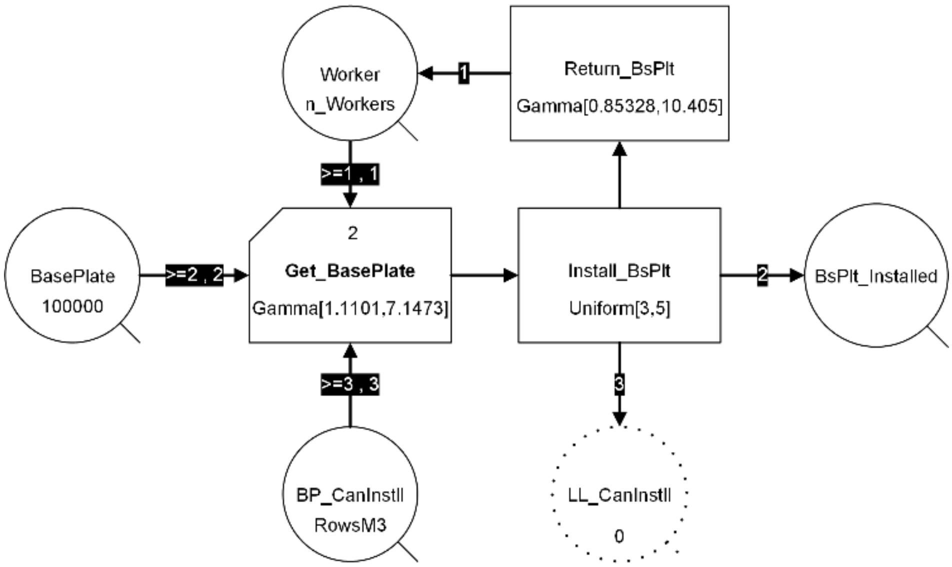

Fig. 2. Activity cycle diagram: base plate installation.

Next, the ledgers and transoms at the lower level of the scaffold are installed, as shown in Fig. 3. Similarly, the worker proceeds to pick up materials in the storage area and deliver them to the set up location (see "Get_Ledger_LL") when there are the adequate resources at "Ledger" and "Worker", and the restriction at "LL_CanInstll". The process passes to "Instl_LowerLv" representing the assemblies of lower-level ledgers and transoms. The worker then reverses back under "Return_ Ledger_LL" to "Worker". The installed materials will be kept in "LL_Installed" while the limitation of working laps is created in "Std_CanInstll" for the next process. Note that the required numbers of ledgers and standards for the installation process are 3 and 2, respectively. Therefore, if one ledger is installed, the worker can install only 2/3 or 0.66 standards. This number is represented in the ACD on the link between "Instl_LowerLv" and "Std_CanInstll". However, to avoid non integer values, we calculated the least common multiple (6) to change the number to an integer. Hence, the number "2" was used on the link instead of 0.66 to indicate that the process will need three rounds (6/2) of ledger installation and two round of standard installation (6/2 = 3 as indicated on the link between "Std_CanInstll" and "Get_Standard" in Fig. 4).

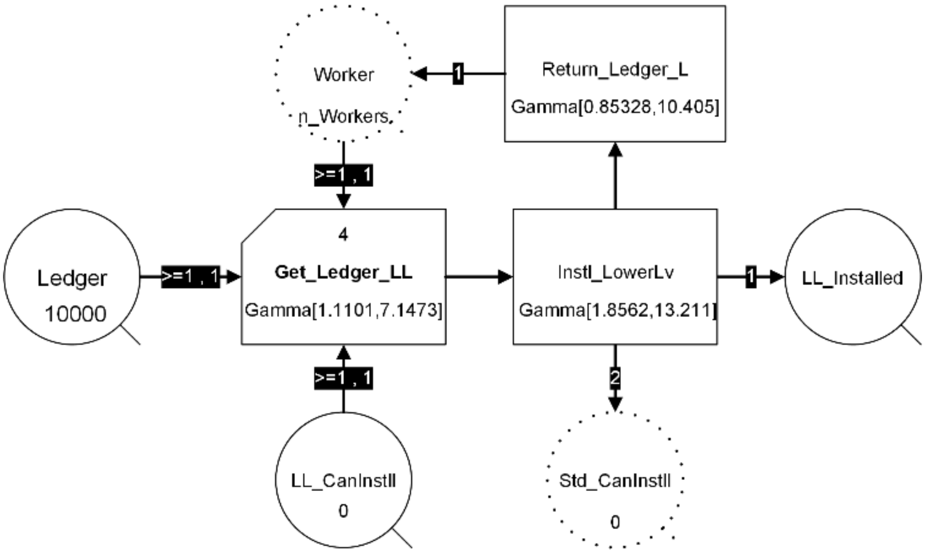

Fig. 3. Activity cycle diagram: lower-level ledger and transom installation.

Figures 4 and 5 also represent the installation processes of the standard, and ledger and transom. The same concept applied for the lower-level ledgers and transoms was adopted here. The number of installed materials is finally collected at "Std_Installed" and "ML_Installed" for the standards, as well as the middle-level ledgers and transoms, respectively. Furthermore, "BP_CanInstll" in Fig. 5 performs as a counter to trigger a new pair of base plates installation ("Get_BasePlate" and "Install_BsPlt" in Fig. 2) when all three middle-level ledgers have been placed.

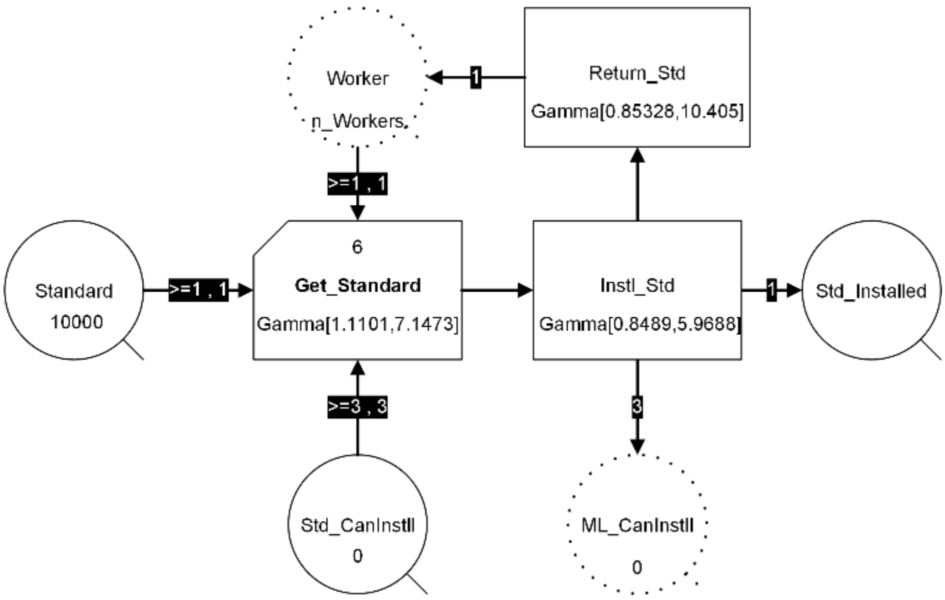

Fig. 4. Activity cycle diagram: standard installation.

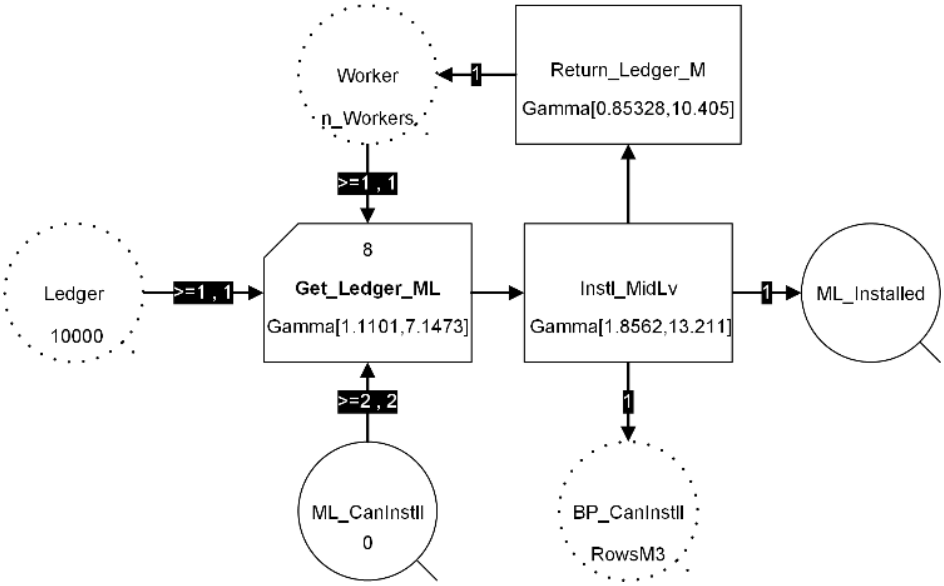

Fig. 5. Activity cycle diagram: middle-level ledger and transom installation.

After completing the structures for the lower and middle levels, the processes for the top-level scaffolding commence. As mentioned, the workers then climb over the middle-level structure to place the ledgers and transoms on the top level (see Fig. 6). This step requires two sets of workers, one for connecting the ledgers and transoms to the existing structures of the top level ("Installer") and the other for delivering and sending the materials to the installers ("Delivery_Worker"). The process starts from some workers who are working on the ground climbing ("Climb") to the top level to install the scaffold elements. The other set of workers, who performed the lower-level construction, will then change their tasks to pick up and deliver the scaffolding elements from site storage to the installers ("Worker_to_Deliv"). The remainder of the workers will continue working on the installation of the lower-level structures

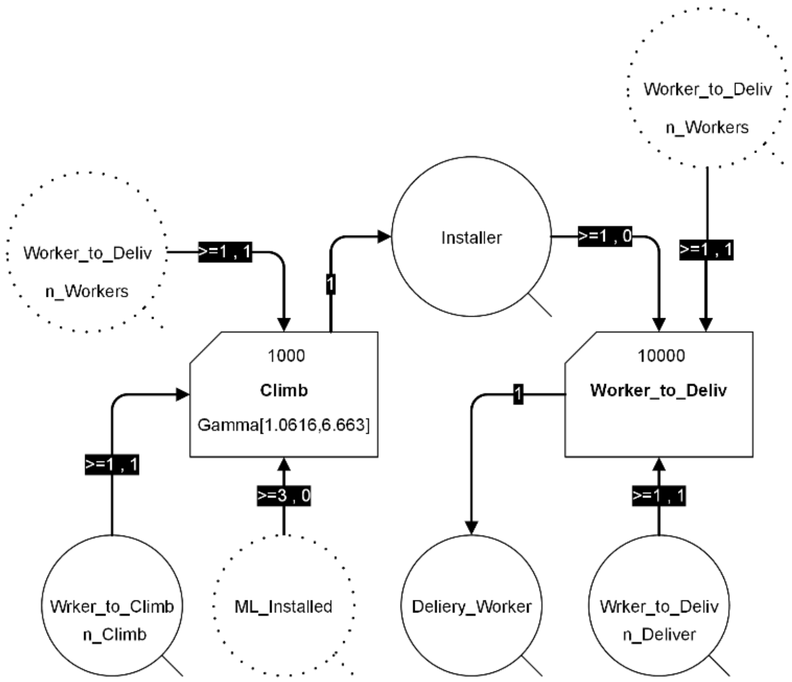

Fig. 6. Activity cycle diagram: climbing to the top level.

The last process is illustrated in Fig. 7 for the ledger and transom installation at the top level. The worker at the ground level picks up the materials and delivers them (see "Get_ Ledger_TL") to the installer under the operation of "Deliver" and sufficient resources in "Installer". However, the start of the delivery activity has to be simultaneously fulfilled by availability in the queue in "Wait_to_Deliv" to ensure that the activity can start merely when an installer is available to receive the material from a delivery worker. After that, "Instl_TopLv" proceeds to connect the materials to the existing standards. The process is repeated over and over until all top-level ledgers and transoms are completely installed for the working bay. The number of finished structures will be stored (“TL_Installed”) and then converted in terms of area (“Area_Installed”) covering 1.44 m² per each bay. The entire process is repeatedly implemented for all the scaffolding bays in the specified area.

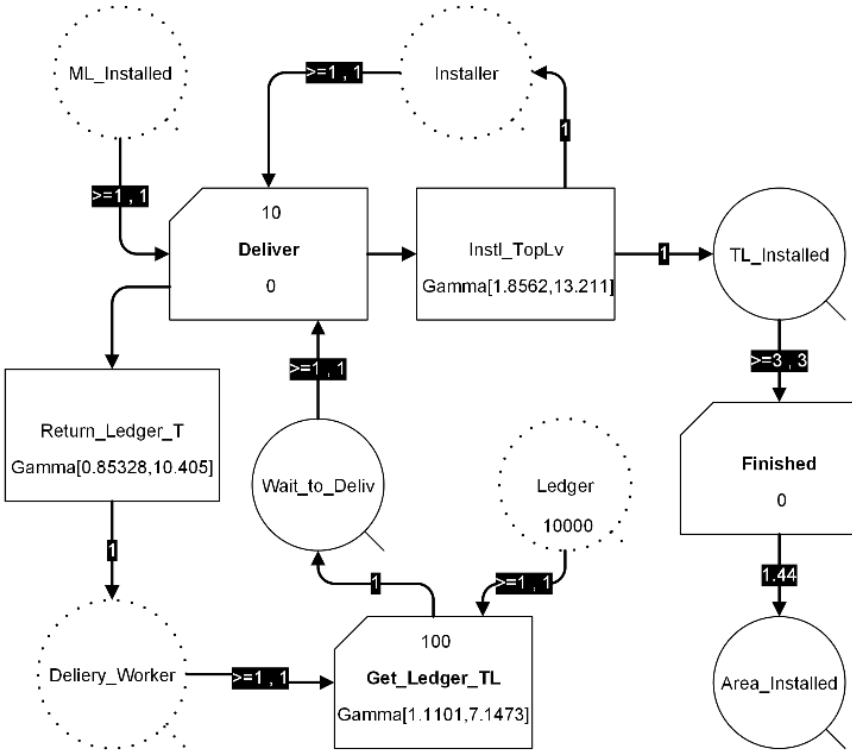

Fig. 7. Activity cycle diagram: top-level ledger and transom installation.

These explanations mainly introduce the activity sequences and resource availabilities. Nevertheless, an activity duration is worth mentioning also as there are uncertainties that lead to different durations for each activity in the construction project. These uncertainties cause variation in activity durations, which is able to be statistically represented in the form of an activity duration distribution. The description of how to address the distribution is presented in the next section.

3.3. Activity Duration Distribution

At least 30 different numbers of durations in performing any activity were collected. Then, all the numbers were statistically analyzed using distribution fitting software (EasyFit) which is capable of selecting an appropriate distribution to handle construction uncertainties. The best fitting model was proposed as a result of the goodness of fit by considering the values of the Kolmogorov-Smirnov and Anderson-Darling approaches. Table 1 shows the selected distribution patterns for activities in this paper.

The distribution patterns and statistical parameters were subsequently entered into the developed ACDs, as shown in Figs. 2 to 7. At this stage, the annotated model was ready for input parameterization and output customization.

Table 1. Selected activity distribution patterns.

Activity	Distribution	Parameters
Get_BasePlate, Get_Ledger_LL, Get_Standard, Get_ Ledger _ML, Get_ Ledger_TL	Gamma	β = 7.1473; α = 1.1101
Return_BsPlt, Return_ Ledger_L, Return_Std, Return_ Ledger_M, Return_ Ledger_T	Gamma	β = 10.405; α = 0.85328
Climb	Gamma	β = 6.663; α = 1.0616
Install_BsPlt	Uniform	[3,5]
Instl_LowerLv, Instl_MidLv, Instl_TopLv	Gamma	β = 13.211; α = 1.8562
Instl_Sta	Gamma	β = 5.9688; α = 0.8489

Of note is that some assumptions were applied in the model construction due to the site and time restrictions of the project case study. First, the initial bay of scaffold installed in a row has a couple of components that are different from consecutive bays as two more standards and base plates are always required at the beginning.

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However, the model was constructed by disregarding that difference for simplicity and generalization. Second, sufficient numbers of scaffolding components were assumed to be separately located close to the installation area in each bay. Therefore, the durations of the "Get Material" and "Return" activities for each bay construction were similar. This may be a little different from resource planning in some real projects where the delivery and return times will vary depending on the distance between the installation area and the predetermined storage location. Third, the durations for assembling the ledger and transom in each level were assumed to be similar because of the very small time difference measured in the real case study.

The next section describes how to apply the DES model to support effective resource allocation in building construction projects. The input variables were initially identified for analysis. The main input is the construction resource, which is related to the three types of workers who deliver, hand in, and assemble scaffolding components. Each type of resource was arranged to achieve high work productivity. The outcome of the simulation analysis was examined in terms of total duration and the idle time for the operations carried out by type of worker and for the total process duration, and total direct labor cost. The number of workers was varied over 500 simulation runs to determine: (1) the impacts of different crew allocation strategies on total duration; (2) the impacts of different crew configurations on the idle time; and (3) an appropriate combination set of workers that satisfied the tradeoff relationship between construction durations and direct labor costs. The analysis results are discussed in the next section.

4. Results and Discussions

The case example involved a 33-stories high-rise building located in Bangkok, Thailand. The average area of installation was approximately 450 m^2 on each floor. The analysis was performed by increasing the number of total workers one at a time from 5 to 12 workers. The number of simulation runs was based on 52 different sets of crew configurations. The results and their analysis are provided below.

4.1. Impacts of Different Crew Allocation Strategies on Total Duration

Two analyses were considered to investigate the impacts of crew assignment on total duration. Fundamentally, the results revealed that for the number of total workers, assigning different amounts of delivery labor had an impact on the total duration which tended to be longer when a larger amount of delivery labor was utilized.

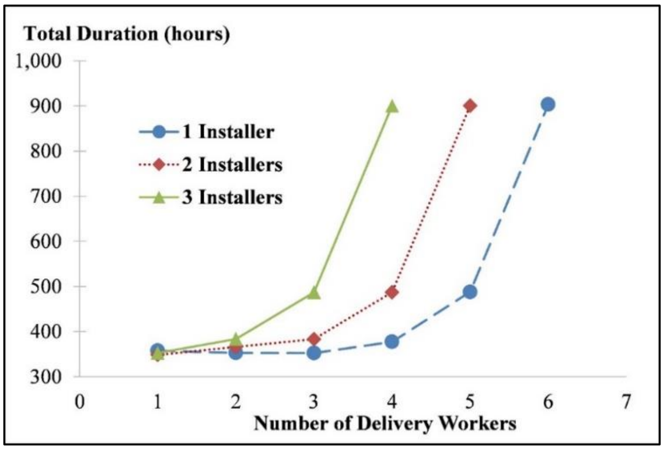

Fig. 8. Total duration for different numbers of delivery workers for total crew of eight workers.

For example, Fig. 8 demonstrates the impacts when the total number of workers is eight with various worker configurations. For four delivery workers on one installation line, the workers for the lower-level activities will be 8 - 4 - 1 = 3 workers. It can be seen in all graphs that increasing number of delivery workers did not meaningfully affect the total duration until a specific number was reached. The total duration on the lower curve (with only one installer), considerably expanded after five delivery workers were employed. A similar situation occurred once four and three delivery workers were assigned to the middle and upper curves, respectively, because beyond these points, the number of workers for the lower-level installation was limited and this could retard progress in the construction process. The delay at the lower level would definitely affect the upper-level construction and therefore, the overall work performance of the crew team. Moreover, the proper crew configuration resulted in a shorter duration when there were at least three workers performing at the lower level in order to have enough base structures.

Figure 9 also illustrates the impacts due to different numbers of installers working on the top-level installation. The results showed a similar trend indicating that different crew configurations could affect total process duration. The entire duration increased substantially after three, four, and five installers were employed for the upper, middle, and lower curve, respectively. Furthermore, Fig. 9 confirmed high productivity when at least three labors worked on the lower-level installation. Figures 8 and 9 show that given the same number of workers, the process can be delayed considerably if work crews are not appropriately configured.

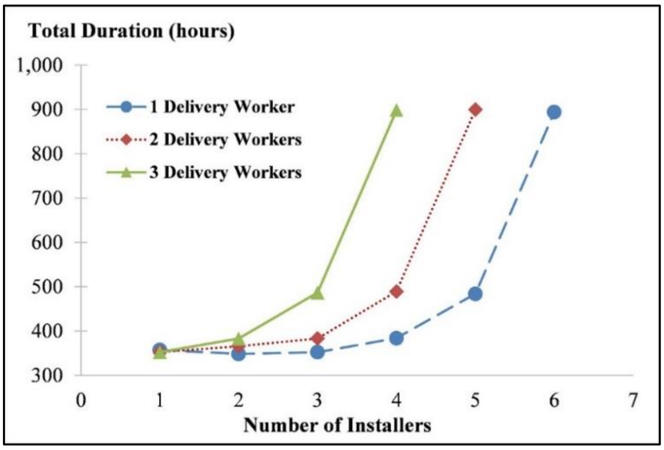

Fig. 9. Total duration for different numbers of installation workers for total crew of eight workers.

Moreover, further investigation indicated that the appropriate number of lower-level workers changed relative to the total number of workers. Possible numbers of lower-level workers tended to increase over a specific range of total number of workers, as shown in Table 2. For example, to keep the process duration under 400 hours in total, the appropriate numbers of lower-level workers were four, five and six when the total numbers of workers were less than six, between seven and nine and more than nine, respectively.

Table 2. Appropriate number of lower-level workers to restrict duration to under 400 hours.

Total worker (persons)	Installer (persons)	Delivery worker (persons)	Lower-level worker (persons)	Total duration (hours)
6	1	1	4	351.8
7	1	1	5	350.2
8	2	1	5	348.4
9	1	3	5	341.5
10	2	2	6	338.6
11	3	3	5	340.7
12	1	5	6	340.4

In addition, the total duration for scaffolding installation at each floor was determined for different numbers of total workers. As shown in Fig. 10, for 5-12 workers, the duration required for a floor varied from 10.3 up to 11.7 hours, respectively, with the lowest value when 10 workers were employed. There was a noticeable impact when a lower numbers of workers was considered resulting in a major change in the project duration. The example showed that the optimal number of 10 workers produced the minimum duration. This confirmed the results of a proper crew configuration on the total construction duration.

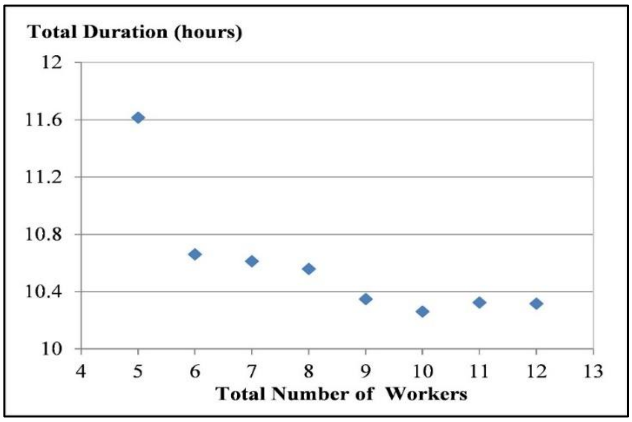

Fig. 10. Total duration versus number of workers.

Furthermore, further investigation presented the greater impact of numbers of lower-level workers over installers and delivery workers, respectively, as shown in Fig. 11 which shows that increasing one lower-level worker resulted in a markedly improved 33-hour productivity improvement. In contrast, there was little impact when only a lower number of workers was employed, while there was no productivity improvement resulting from an increase in the number of delivery workers. Moreover, this was confirmation of the suitable proportion between the numbers of installers and delivery workers.

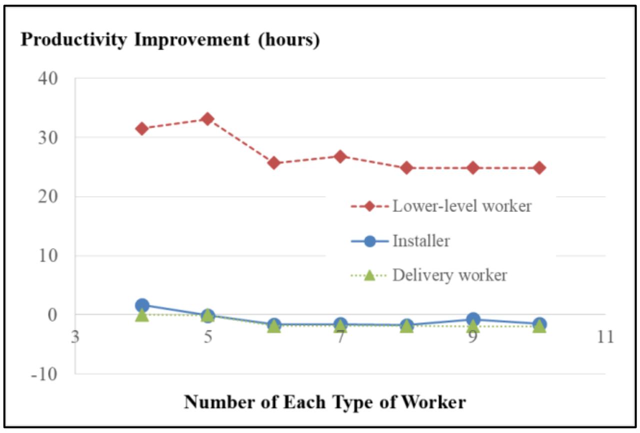

Fig. 11. Impact of different worker type on total duration.

4.2. Impacts of Different Crew Allocation Configurations on Idle Time

This section considers the impacts of crew configurations on the idle time of each worker type, and therefore on total non-productive time. Figures 12-14 illustrate the total idle time for any type of worker with different crew configurations. Each figure illustrates the impacts on the labor idle time due to the variation in the number of workers. The configuration i-j-k represents a crew fleet consisting of i installers, j delivery workers and k lower-level workers. Figure 12 shows that an appropriate resource proportion for effective performance was achieved when the number of either installers or delivery workers did not exceed two.

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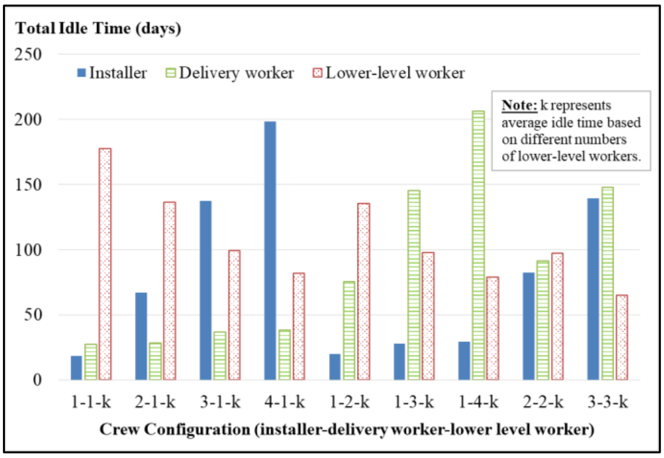

Fig. 12. Total idle time at different crew configurations by changing number of lower-level workers.

Based on Fig. 13, there was no material idle time for lower-level workers if a small number of lower-level workers performed the construction task. In addition, the potential proportion of delivery to lower-level workers of 1:3 or higher produced the most effective performance. Furthermore, the installers and delivery workers worked together to perform their first level tasks, so their relationship was quite important to the work achievement. Similarly, Fig. 14 confirms the importance of the promising ratio between the numbers of installers to delivery workers. Detailed consideration indicated that the appropriate crew configuration of 1:1:3 led to the minimum total idle duration.

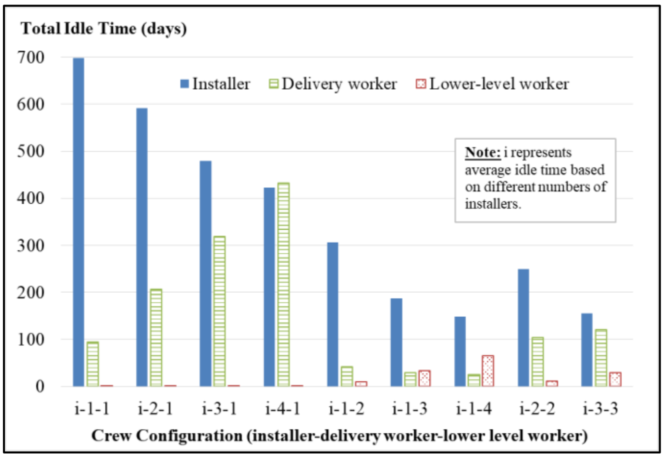

Fig. 13. Total idle time at different crew configurations by changing number of installers.

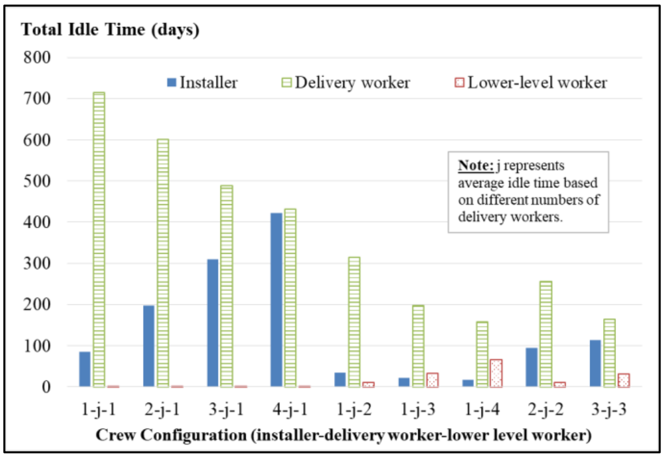

Fig. 14. Total idle time at different crew configurations by changing number of delivery workers.

Of note is that the crew configuration with the shortest duration did not necessarily provide the minimum idle time, due to different numbers of total workers employed. The crew configuration with the shortest duration consisted of two installers, two delivery workers and six lower-level workers for a total workforce of 10. On the other hand, the lowest idle time occurred using five workers with the ratio 1:1:3. Thus, in order to have the shortest duration, the workforce requires a high number of total workers that results in a large amount of idle time during the construction process, and therefore higher labor costs.

Figures 15 to 17 introduce the results from further investigation regarding varying the number of lower-level workers. The findings confirmed the robust correlation between installers and delivery workers. The proper ratio between these two worker types substantially improved their idle reduction (Figs. 15 and 16), but had little impact on the idle time for lower-level workers (Fig. 17).

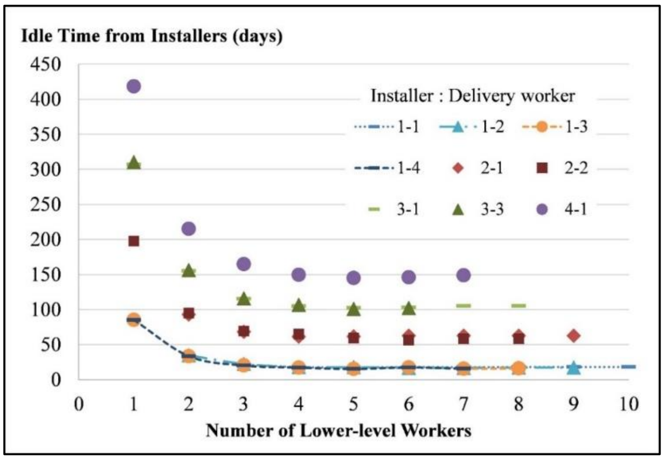

Fig. 15. Impact of crew configuration on idle time of installers.

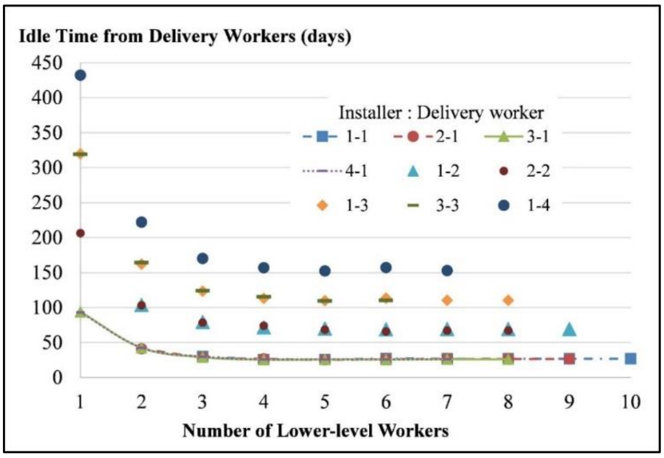

Fig. 16. Impact of crew configurations on idle time of delivery workers.

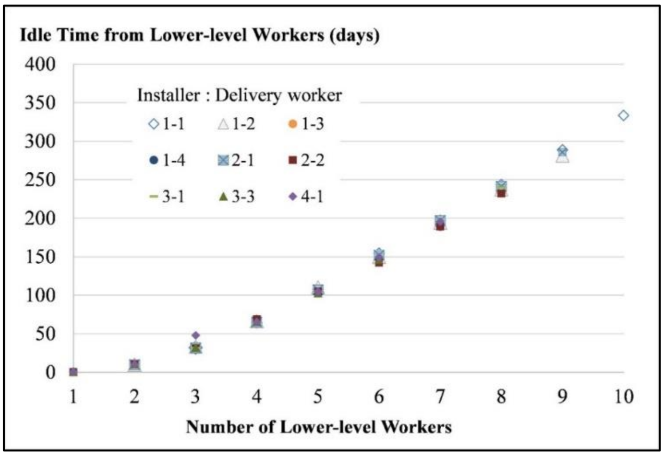

Fig. 17. Impact of crew configuration on idle time of lower-level workers.

In addition, the findings indicated that project productivity improvement was dependent on two main attributes: (1) an appropriate crew configuration for installers and delivery workers performing the second level installation tasks; and (2) the first level installation was mainly associated with the work progress of lower-level workers. Therefore, there was a need to harmonize the workflow and progress resulting from both attributes to increase work productivity.

4.3. Tradeoff Relationship between Construction Duration and Direct Labor Cost

This section introduces the tradeoff relationship between total labor cost and total duration of the scaffolding installation process. Figure 18 illustrates the wide range of optimal crew configurations capable of minimizing the cost and duration, with the two cross marks indicating the dominant solutions while the points on the solid line represent the feasible solutions lying on the Pareto frontier. A point on the blue line suggests a feasible crew configuration leading to the trade-off decision between cost and time that must be considered by the project manager to enhance construction productivity.

A non-dominated solution could be selected for implementation based on the important weights given to the two planning objectives (total cost and project duration in this paper). In Fig. 18, the number to the left of each point represents the number of workers used for the scaffolding assembly. Among all feasible solutions, the highest labor cost but shortest duration is represented when the number of workers equals 10. On the other hand, the crew configuration spending the lowest cost requires the lowest number of workers but results in the longest duration.

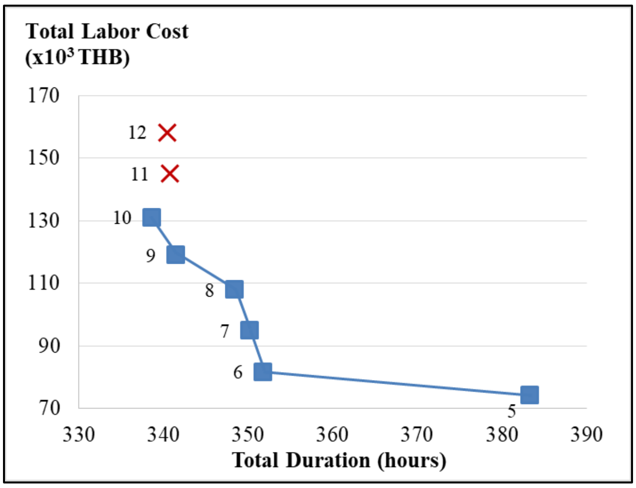

Fig. 18. Tradeoff relationship between duration and cost.

Based on all these findings, the project engineer can use the simulation analysis results to assist in decisions regarding project management and crew allocation for scaffolding productivity improvement. The construction supervisor can properly allocate the number of workers according to the solution recommended from the model runs. Worker tracking and monitoring are required to verify that the workers are following the supervisor's instructions and to monitor work production. Even though the model was applied at the micro level of case study analysis, the application of the developed paradigm is proficient in proposing the effective worker allocation scheme without impeding the current construction operations. The supervisor can utilize the model as a decision-support tool for managing crew allocation and the configuration of the scaffolding process and can further implement this approach in other construction processes.

Nevertheless, it is noteworthy that verifying the analysis results using a real construction project is very difficult and almost impossible, since it requires strong cooperation and commitment from the contractor to allow the routine operations to be changed and interrupted that will affect work productivity and project completion time. This is one of main reasons for implementing the DES technique in the existing research to simulate the complex construction processes and further perform computerized modification on the original simulation model without disturbing the current project schedule. As a result, the verification in this paper was performed by investigating the differences between the actual and simulated durations of the original scaffolding installation task in one specific area. The verification results showed only small variation in the construction durations between real practice and simulation analysis, as the onsite operation took around 2.4 minutes to complete a 1.44 m^2 scaffolding installation (one bay of scaffolding) while the simulation result resulted in installation duration of 2.23 minutes for the same area. The difference was small and acceptable although some possible variations arose due to the model assumptions and the time measurements. Moreover, the numerical result of the installation duration from the simulation run can be compared with the statistical cost data shown in RSMeans Building Construction Cost Data [33]. The productivity data of scaffolding assembly was retrieved and the duration was then estimated based on similar project characteristics and indicated the expected productivity rate at 270 m^2 per day, with an average of 2.57 minutes to install each bay.

5. Conclusions

This paper enhances the current body of knowledge in the area of crew allocation to promote work productivity improvement by adopting the DES technique, which is capable of handling the complexity and volatility of construction processes. The case study of scaffolding installation for a high-rise building construction project in Thailand was introduced with through the implementation of EZStrobe, a promising DES tool. The results highlighted the performance and capabilities of the DES technique in simulating the multiple systems and therefore effectively allocating the resources. The analysis showed an appropriate combination of all types of required workers in the tested scaffolding process that was capable of minimizing both construction cost and time. In addition, the importance of the types of associated workers was indicated according to the magnitude of the impact on the total process and idle times. This could guide the project manager to avoid assigning an excessive number of workers to some prospective activities. The proposed paradigm should prove useful in effectively allocating construction resources and enhancing work productivity.

The research study presented in this paper can be extended to other construction activities in either building or infrastructure projects to further confirm the application of the proposed paradigm. Moreover, advanced development can be examined to include the costs of materials and equipment in the construction cost to provide a comprehensive viewpoint on the time-cost trade-off relationship.

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Nathee Athigakunagorn received the B.Eng. and M.Eng. in Civil Engineering from Kasetsart University, Bangkok, Thailand in 2001 and 2006; and the M.S.C.E., and Ph.D. in Civil Engineering from Purdue University, Indiana, USA in 2012 and 2015, respectively.

He currently holds an academic position at the Faculty of Engineering at Kamphaeng Saen, Kasetsart University, Thailand, where he was appointed to an assistant professor since 2017. His research interest includes construction process simulation, construction decision under uncertainty, and highway infrastructure asset management and policy.

Dr. Athigakunagorn was a recipient of the Best Young Researcher Award at the 18th International Conference on Civil and Environment Engineering (ICCEE) at Pukyong National University, Busan, South Korea in 2019.

Charinee Limsawasd received the B.Eng. and M.Eng. in Civil Engineering from Chulalongkorn University, Thailand, in 2001 and 2007; and the Ph.D. in Civil Engineering from Florida International University, FL, USA, in 2016.

During her Master's degree, she was a Teaching Assistant at the Department of Civil Engineering, Chulalongkorn University. From 2011-2016, she was a Graduate Assistant at OHL School of Construction, College of Engineering and Computing, Florida International University. After receiving her Ph.D., she worked as a lecturer and has been appointed to an Assistant Professor with the Civil Engineering Department, Faculty of Engineering at Kamphaeng Saen, Kasetsart University, Thailand since 2017. Her research interests include sustainability in construction, optimization and simulation modeling, and construction contracts and bidding.