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OPTIMIZING CONSTRUCTION PRODUCTIVITY AND RESOURCES IN BUILDING PROJECTS UNDER UNCERTAINTY

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Abstract: Construction duration is always one very crucial unknown that every party involved in construction projects attempts to determine. However, with resource limitation and construction uncertainty, it is impossible to have the least construction duration and have an accurate estimate of construction activities' durations. This leads to an inefficient resource allocation that has a significant impact on a project's success. To this end, there is a need of a novel and innovative approach that is able to support an estimation of construction duration under uncertainty, as well as an optimization of construction productivity and available resources to obtain the highest benefits.

This paper aims to present a new application of discrete-event simulation in enhancing work productivity of a construction activity. The construction process in a high-rise building was selected as an example to demonstrate the proposed framework and its capabilities in efficiently allocating construction resources to reduce an activity duration under uncertainty. The final result presents total construction time, labor waiting time and total construction cost under different resource allocation strategies. Moreover, the analysis also illustrates a relationship between construction productivity, in terms of construction duration and waiting time, and allocated resources. This study should prove useful to contractors in applying the concept of discrete-event simulation to support their decision making during resource acquisition and allocation processes.

1 INTRODUCTION

The construction industry frequently encounters cost and time overruns. Their seriousness and impacts on construction projects have been reported among several nations. Statistically, the public projects in Qatar had more than a 50% cost increase and a 70% time overrun over the past decade (Senouci et al. 2016). In addition, the record shows the time overrun with an average of 35% and a maximum of 66% deviated from the targeted project duration in Malaysia (Memon et al. 2011). Hundreds of public works in Nevada were analyzed and the result revealed almost 5% and 22% in project cost and schedule overruns, respectively (Shrestha et al. 2013). All of these obstacles are inherently caused from the complexity and dynamic nature of construction projects (Mills 2001). Construction uncertainty has been acknowledged from its negative consequences that greatly correlate to several factors, such as weather conditions, material quality, and labor productivity (Mills 2001).

Various existing studies have strived to investigate and manage uncertainty in construction (e.g. Akintoye and MacLeod 1997; Baloi and Price 2003; Carr and Tah 2001; De Meyer et al. 2002; Mustafa and Al-Bahar 1991; Ward and Chapman 2003). Based on Kaming et al. (1997), the related-productivity factors ranked in the top tier that have predominant impacts on time and cost overruns are the poor labor productivity and inaccurate prediction of workmanship productivity. As such, besides the concept of uncertainty management, an improvement of labor productivity and an increased number of resources can be two other strategies that have a direct impact on increasing the productivity rate. However, implementing these strategies can result in two main challenges. First, uncertainty always causes an inaccurate estimation of labor productivity and then activity duration. The simple-yet-accurate technique is needed to facilitate a duration prediction under uncertainty. Second, crashing duration usually comes with the cost increase as a result of higher resource utilization. The optimum resource allocation should be considered to balance the purpose of cost and time in construction projects.

In order to address the first challenge, this paper proposes the application of discrete-event simulation (DES) as a need of a simulation technique that is capable of analyzing complex construction systems and incorporating uncertainty. The DES has been acknowledged as a promising modeling technique that adopts the computer simulation in modeling an electronic realistic prototype in order to represent a real operation of a complex system (Lu 2003). In addition, an optimization approach can be applied to address the second challenge. While the construction time and cost tend to be counterbalanced, adding a number of resources always leads to an increase of construction cost but does not always reduce the duration. The optimal time-cost equilibrium is expected for an effective resource allocation and a reveal of resource dissipation. However, a very limited number of past studies have applied DES on building works. They have mostly focused on heavy construction projects with an operation of heavy construction equipment (e.g. Ahn et al. 2010; Hassan and Gruber 2007; Hassan and Gruber 2008; Lu 2003; Shawki et al. 2015; Smith et al. 2015; Zhang 2013).

The objective of this paper is to present a new application of DES in enhancing work productivity in building construction projects. The scope of this study emphasizes the building work, in which a skilled-labor or workman is hired. The scaffolding work is adopted here as an application example to demonstrate the performance and capabilities of the proposed framework in facilitating the crew allocation subject to the construction uncertainty. The research methodology starts from the development of the activity cycle diagram (ACD) that represents the complex operational system of the case study. Then, an analysis is performed in order to evaluate effectiveness and optimality of the resource strategies, along with a consideration of resource waiting duration, total duration to complete the construction process, and total cost.

The rest of this paper is organized as follows. The next section presents the literature review and theoretical knowledge on DES. The EZStrobe, one of the powerful simulation systems selected for the simulation modeling in this paper, is then presented. Afterwards, an application example is introduced, followed by the analytical findings in the results section. The conclusions and limitations of the study are also given in the last section.

2 DISCRETE-EVENT SIMULATION OVERVIEW

This section presents the past literature on the theoretical concept and application of a DES technique in order to help the researcher in developing an essential basic knowledge, as follows.

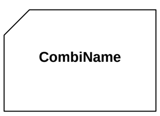
Discrete-even simulation (DES) is stated as “the modeling of a system as it evolves over time by a representation in which the state variables change only at a countable number of points in time” (Law and Kelton 1991). The complex and dynamic problems can be advantageously investigated from the systematic experiments at a more controllable, flexible and low-cost environment (Martinez 2009; Wang and Halpin 2004). DES is also capable of predicting the future status of a real system as a result of the computer modeling development that represents its realistic data and conditions (Lu 2013). In fact, DES has been adopted in several research areas. For example, Legato and Mazza (2001) applied DES in the logistic activities of vessels at a container terminal. Jacobson et al. (2006) proposed DES applications on health care clinics and integrated health care systems. Additionally, it was implemented in Wu and Wysk (1989) in order to control planning and scheduling of a manufacturing system.

In the construction industry, DES has been widely used to analyze complex operations in construction projects over the past decades (Martinez and Ioannou 1999). According to Martinez (2009), it has been acknowledged as a powerful simulation technique that is capable of analyzing processes or operations of construction projects. Since an emerging of CYCLONE by Halpin in 1977, several simulation systems have been developed to facilitate an analysis over the complicated, dynamic, and challenging nature of construction processes, such as STROBOSCOPE (Martinez 1996) , EZSTROBE (Martinez 1998), and Visual SLAM (Pritsker and O'Reilly 1999). The application of DES in the construction area has been examined over a significant number of past studies (e.g. Ahn et al. 2010; Jiradamkerng 2016; Zhang 2013).

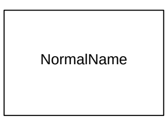
3 EZTROBE SIMULATION SYSTEM

Due to its simplicity and ease, EZStrobe was introduced in this study for modeling complex and dynamic construction operations. The following paragraphs will briefly describe its theoretical concept and model construction.

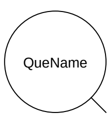
EZStrobe was developed by Martinez (1998) with a simple and easy-to-learn graphical interface that is aimed to supplement the use of STROBOSCOPE. EZStrobe employs the Microsoft Visio interfaces for model construction, with the operation running on the STROBOSCOPE platform. Thus, a modeller does not need to conduct advanced coding for the simulation analysis. In order to simulate a real system, the activity cycle diagram first must be constructed, in which construction activities, resources, and their interactions will be presented. The EZStrobe elements can be categorized with three basic shapes: rectangle, circle, and link with representations of Combi, Normal, Queue, Fork, and Link. Their details and explanations are given as follows:



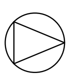
A Combi is named after a “Conditional Activity” that represents a constrained activity that can start upon an availability of required resources. This means the number of resources in the preceding Queues need to be checked in order to start Combi. It can only follow Queues, but be placed before any other node except a Combi.



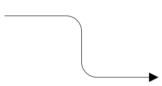
A Normal or “Bound Activity” is named to represent an unconstraint activity that can start upon the completion of preceding activities. A Normal can follow any node other than a Queue, and be placed before any node except a Combi.



A Queue is named to represent where idle resources are stored for use in a succeeding Combi. A Queue can follow any other node other than a Queue. It also allows only a Combi for a succeeding activity.



A Fork represents a probabilistic element that initiates a path selection to the succeeding element. The path will be selected based on the probabilistic value on the fork-towards-successor links, called the Branch link.



A Link represents a connectivity between different activities and queues. There are three types of Link in EZStrobe: Draw Link, Release Link, and Branch Link. A Draw Link connects between a Queue and Combi with representations of the content in the predecessor Queue and an amount of resources released through the Link. A Release Link connects an activity to any other node except a Combi, showing an amount of resources released to successors. A Branch Link connects a Fork to any other node except a Combi with a representation of a probabilistic value on it.

The uncertainty in a construction process can impact the activity duration to complete the task. EZStrobe allows a modeller to integrate uncertainty and the dynamic nature of construction in the simulation model by inputting a probabilistic distribution formula that can represent a realistic condition of an activity duration. The duration of each instance will then be randomly selected from the predefined probabilistic distribution.

4 APPLICATION EXAMPLE

An application example is analyzed in this study to demonstrate the capabilities of the proposed framework in integrating uncertainty and effectively allocating resources in order to improve work productivity in construction projects. The example aims to search for potential resource allocation strategies that can be best fulfilled for both the cost and time objectives under construction uncertainty. This section introduces a case study of building scaffolding work in Thailand. All duration distributions used in this study were presumably created based on an availability of site investigation data. The ACD of the application example was constructed, as shown in Figure 1.

In this study, an installation of the scaffolding is needed in order to be a temporary structure for supporting the post-tension slab of the building construction work in Thailand. A set of the scaffold has a width of 1.2 m, a length of 1.8 m, a height of 1.7 m. One set of scaffolding work employs 1 set of crew that consists of 5 workers (Man1, Man2, Man3, Man4, and Man5) in order to install a two-level scaffold. The process can be categorized into 5 cycles corresponding to the responsibility of each worker, as follows:

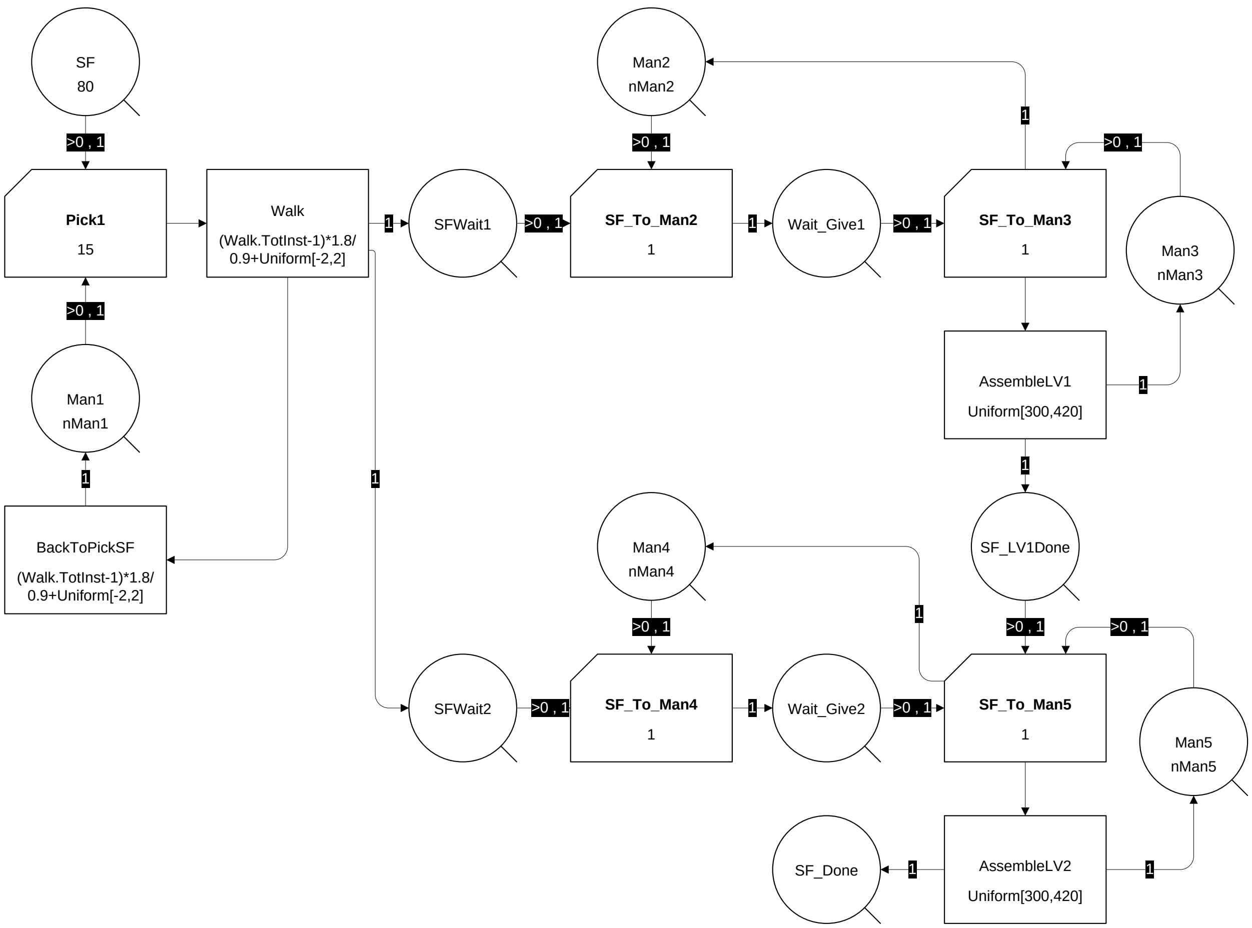


Figure 1: Activity cycle diagram for application example: building scaffolding

- Man1 collects two scaffolds (see the “Pick1” COMBI) from the storage area at the “SF” QUEUE. He then carries the scaffolds (see the “Walk” COMBI) and waits for Man2 and Man 4 to pick up the scaffolds for level 1 and level 2 at the “SFWait1” and “SFWait2” QUEUE, respectively. After that, he will go back to pick up a new set of scaffolds (see the “BackToPickSF” NORMAL).

- Man2 carries the scaffold at an installation location (see the “SF_To_Man2” COMBI). He then waits at the “Wait_Give1” QUEUE before giving the scaffold to Man3 at the “SF_To_Man3” COMBI. Afterwards, he moves back to an original position for gathering a new scaffold from Man2.

- Man3 gets the scaffold from Man2 to install for level 1 at the “AssembleLV1” NORMAL. The process will be repeated mainly on Man2 and Man3 for the 1- level scaffolds.

- Similarly, Man4 and Man5 will be assigned for the job in level 2. However, it is worth noting that the installation work in level 1 needs to be completed before starting level 2 for any bay of scaffold (see the “SF_LV1Done” QUEUE).

5 RESULTS

In this section, the base case was defined as the normal resource allocation strategy, in which one worker was assigned for each type of labor (i.e. Man1, Man2, Man3, Man4, and Man5). The base case was run at 200 iterations and the simulation results can be illustrated as the screenshot in Figure 2. The total construction time to complete the process, total waiting time of workers, and total construction cost were calculated and analyzed at each iteration. Considering the calculated waiting time and activity, the result from the base case suggests the author should categorize the labors into three groups, which are Man1, Man2&4, and Man3&5.

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** Calculated results after simulation **

Time to Complete the Process in Hours  : 8.18807
Total of Ave Waiting Time of Activities: 690.451
Total Cost of the Operation            : 716.456

Statistics report at simulation time 29477
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Queue	Res	Cur	Tot	AvWait	AvCont	SDCont	MinCont	MaxCont
Man1	ezs	1.00	81.00	180.38	0.50	0.50	0.00	1.00
Man2	ezs	1.00	81.00	14.67	0.04	0.20	0.00	1.00
Man3	ezs	1.00	81.00	9.75	0.03	0.16	0.00	1.00
Man4	ezs	1.00	81.00	5.31	0.01	0.12	0.00	1.00
Man5	ezs	1.00	81.00	7.04	0.02	0.14	0.00	1.00
SF	ezs	0.00	80.00	5209.86	14.14	19.97	0.00	80.00
SFWait1	ezs	0.00	80.00	8481.56	23.02	11.83	0.00	37.00
SFWait2	ezs	0.00	80.00	9007.02	24.44	11.71	0.00	39.00
SF_Done	ezs	80.00	80.00	14429.70	39.16	23.41	0.00	80.00
SF_LV1Done	ezs	0.00	80.00	176.34	0.48	0.56	0.00	2.00
Wait_Give1	ezs	0.00	80.00	351.61	0.95	0.21	0.00	1.00
Wait_Give2	ezs	0.00	80.00	361.09	0.98	0.14	0.00	1.00

Activity	Cur	Tot	1stSt	LstSt	AvDur	SDDur	MinD	MaxD	AvInt	SDInt	MinI	MaxI
AssembleLV1	0	80	32.00	28346.83	357.59	36.50	301.18	418.34	358.42	36.70	302.18	419.34
AssembleLV2	0	80	382.96	29076.88	360.34	35.69	303.69	419.79	363.21	34.06	304.69	420.79
BackToPickSF	0	80	30.00	14709.60	78.80	46.54	0.03	156.98	185.82	91.76	30.03	342.52
Pick1	0	80	0.00	14523.86	30.00	0.00	30.00	30.00	183.85	91.72	30.03	341.98
SF_To_Man2	0	80	30.00	27982.27	1.00	0.00	1.00	1.00	353.83	52.18	30.03	419.34
SF_To_Man3	0	80	31.00	28345.83	1.00	0.00	1.00	1.00	358.42	36.70	302.18	419.34
SF_To_Man4	0	80	30.00	28729.72	1.00	0.00	1.00	1.00	363.29	34.03	304.69	420.79
SF_To_Man5	0	80	381.96	29075.88	1.00	0.00	1.00	1.00	363.21	34.06	304.69	420.79
Walk	0	80	30.00	14553.86	77.03	46.33	0.00	155.74	183.85	91.72	30.03	341.98

Figure 2: Statistics report for base case simulation run

Corresponding to each scenario, the analysis was first performed to increase a number of crews from the base case by 1 to 5 for each group of labors. The number of simulation runs was totally based on the different 125 crew configurations. It was found that the minimum construction time was 1.78 hours by various crew configurations. The crews that consist of 4 Man1, 1 Man2&Man4, and 5 Man3&Man5 spent the lowest cost to complete the construction at $161, while the crews that consist of 3 Man1, 1 Man2&Man4, and 5 Man3&Man5 had the lowest waiting time at 7.80 minutes.

For simplicity, two of the labor groups would be fixed and the crew in the other group would then be varied from 1 to 5 in order to investigate the impact of the crew configuration on the total construction time to complete the process and the total waiting time of workers. For instance, Figure 3(b) illustrates the case that the number of Man1, Man3&Man5 is fixed to 1 crew while Man 2&Man4 is increased from 1 to 5 crews (i.e., 1-n-1 crew configuration). Note that the total construction cost was omitted in the figure because its trend was similar to either the total construction time to complete the process or the total waiting time of workers.

Figure 3(a) shows that, when Man 2 to Man5 were all fixed to 1 crew (i.e., n-1-1 crew configuration), an addition of Man1 cannot improve the productivity of the scaffolding installation process. In fact, increasing Man1 merely exacerbated the productivity by increasing the total waiting time. This was also true for the 1-n-1 case, even a very slight improvement in the total construction duration was noticed when adding more Man2 (see Figure 3(b)). For case 1-1-n in Figure 3(c), increasing both Man3&Man5 from 1 to

2 crews decreased the total duration form 8.22 hours to 4.29 hours. Nevertheless, increasing this crew group more than 2 crews did not shorten the total duration. This instead increased the crew total waiting time and hence the cost of the operation.

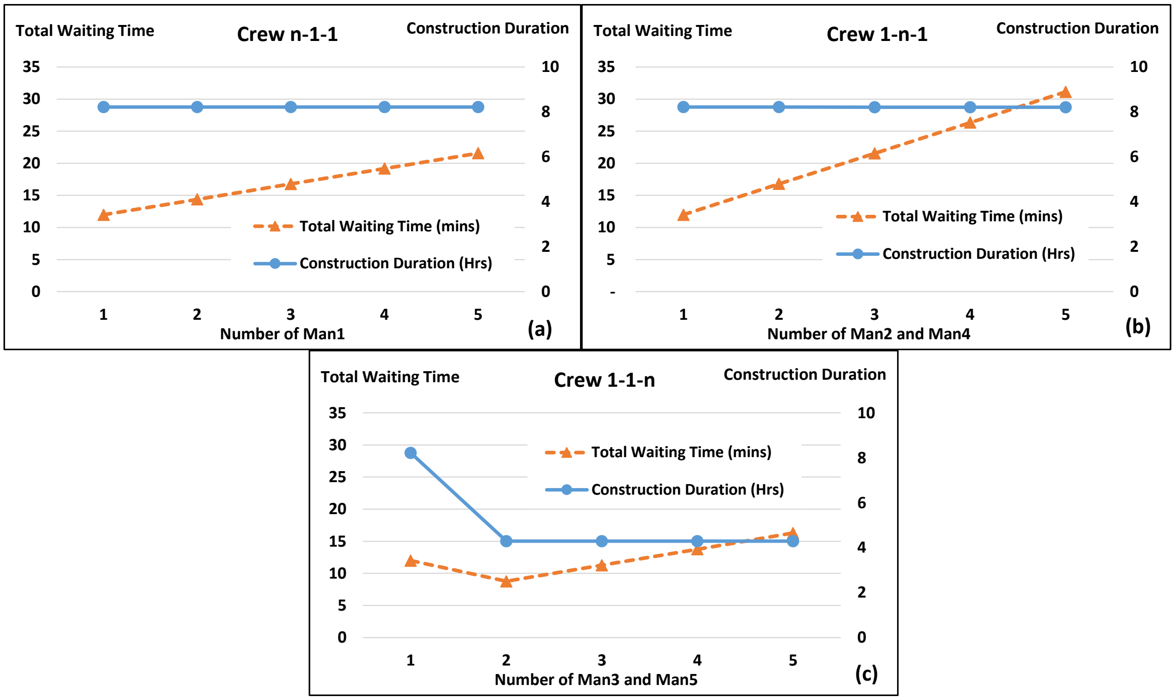

Figure 3: Variations of total construction time and total waiting time for different crew configurations in case (a) n-1-1; (b) 1-n-1; and (c) 1-1-n

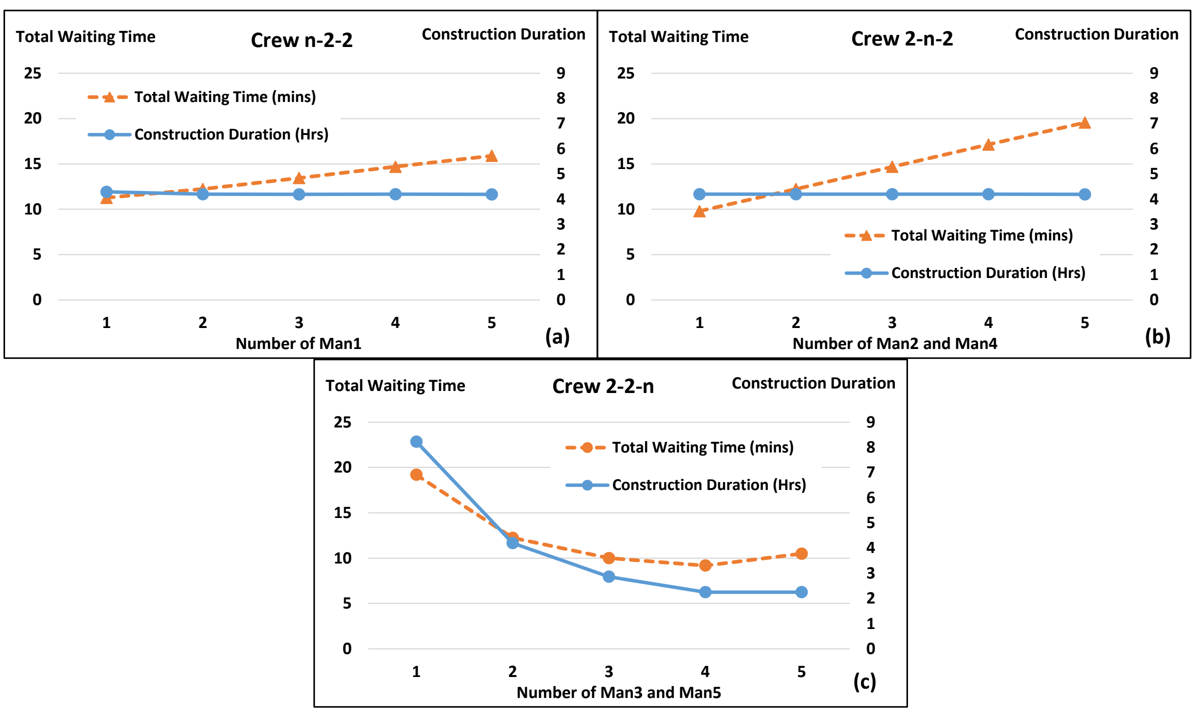

Figure 4: Variations of total construction time and total waiting time for different crew configurations in case (a) n-2-2; (b) 2-n-2; and (c) 2-2-n

The variations of total construction time and total waiting time for case n-2-2 and 2-n-2 crew configuration were reported in Figure 4(a) and Figure 4(b), respectively. The figures showed that all of these crew configurations yielded the total construction time of 4.19 to 4.20 hours with no significant change in the process time when the crew was varied. These, consequently, were the same trends as found in case n-1-1 and 1-n-1 crew discussed in the above-mentioned paragraph. However, Figure 4(c) indicates that adding Man3& Man5 could not only cut the duration from 8.22 to 2.25 but also reduce the crew waiting time for case 2-2-n. The reductions in construction duration and waiting time is also likely to significantly decrease the construction cost. Note further that the optimal scheme for case 2-2-n is when n equals to 4, which gave the lowest construction cost and total waiting time at $650 and 9.20 minutes.

Next, the trends of changing a number of Man1 when fixing the numbers of Man2&4 and Man3&5 at 3, 4, and 5 crews, respectively, were considered (see Figure 5(a), 6(a), and 7(a)). They insignificantly demonstrate a positive impact of Man1 on the construction time and waiting time after adding 2 crews for operating the task. On the other hand, increasing a number of Man2&Man4 never generates a better work performance, as they always give a steady construction time and waiting time no matter of how much a number of Man2&Man4 was assigned. This finding is also applicable over Figure 5(b), 6(b), and 7(b).

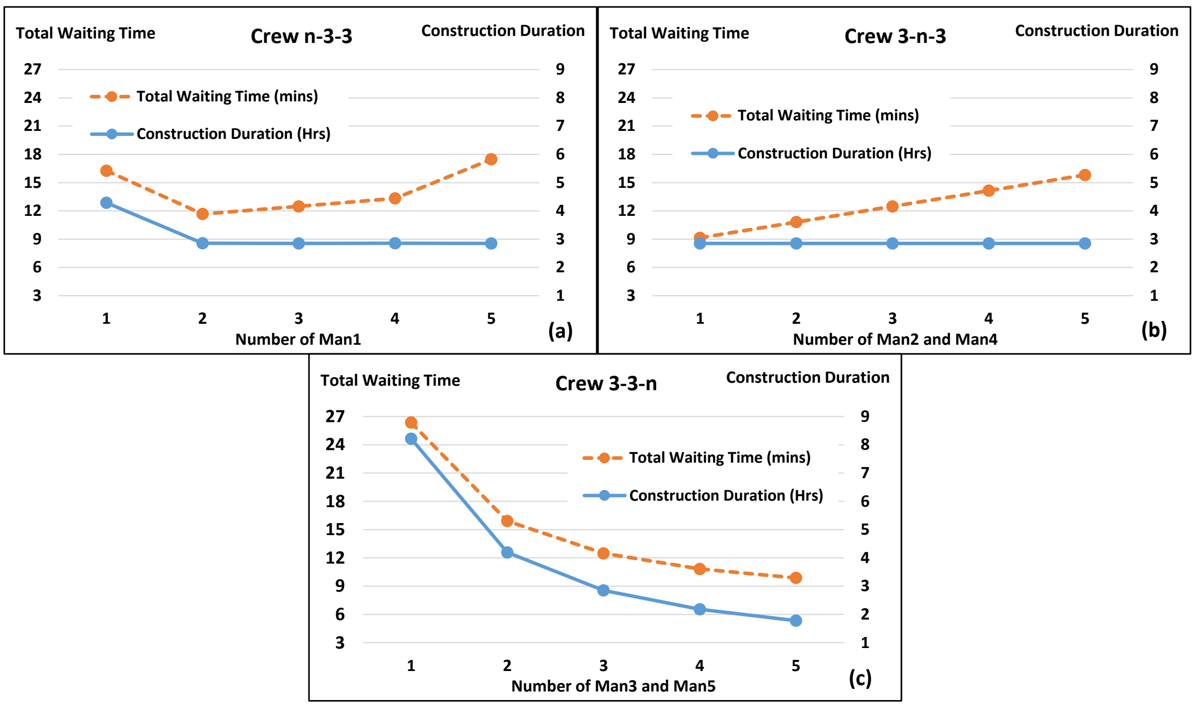

Figure 5: Variations of total construction time and total waiting time for different crew configurations in case (a) n-3-3; (b) 3-n-3; and (c) 3-3-n

Considering Figure 5(c), 6(c), and 7(c), the change in a number of Man3&Man5 presents productivity improvement of the construction process. The construction time and waiting time tend to be smaller when increasing a number of crews in this group.

Moreover, some findings have been observed when taking into account the same series of crew configurations (i.e. Case n-1-1, n-2-2, n-3-3, n-4-4, and n-5-5). This observation aligns with the optimal crew configuration discussed earlier. The results can be summarized and concluded as follows.

- Consider Figure 3(a) to Figure 7(a). It is found that adding Man1 can help reduce the construction duration only when the number of crews is large (e.g., case n-4-4 in Figure 6(a) and case n-5-5 in Figure 7(a)). However, this also increases the total construction cost.

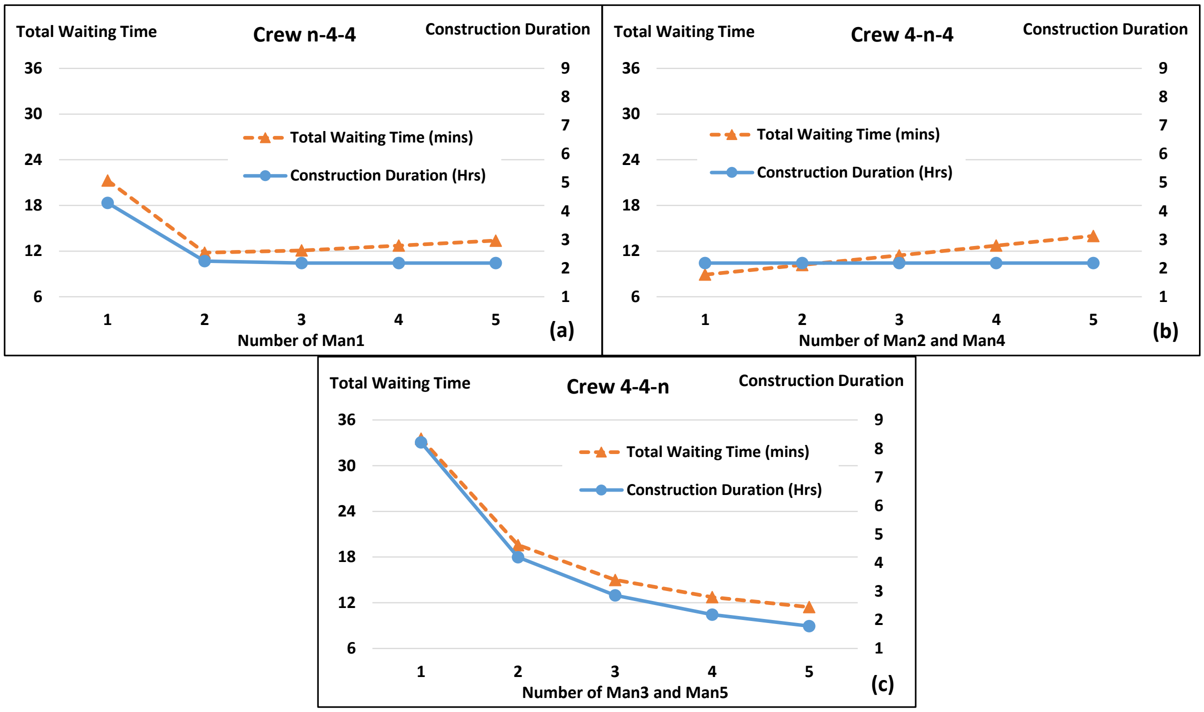

Figure 6: Variations of total construction time and total waiting time for different crew configurations in case (a) n-4-4; (b) 4-n-4; and (c) 4-4-n

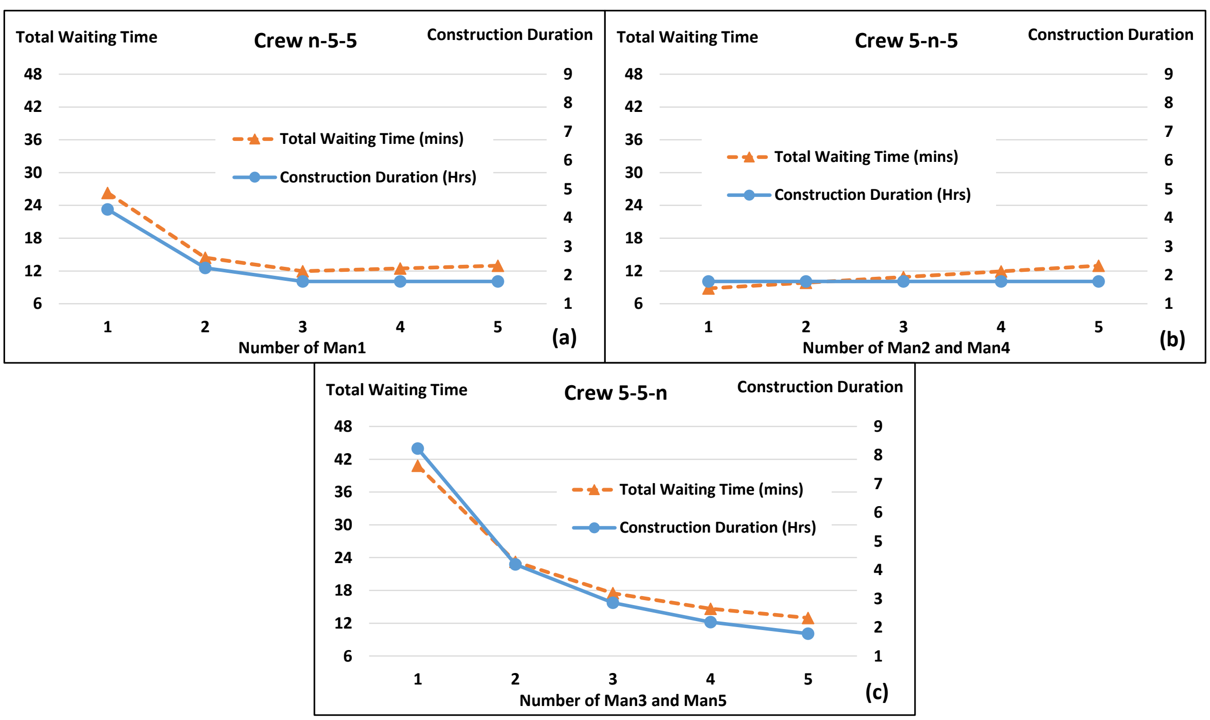

Figure 7: Variations of total construction time and total waiting time for different crew configurations in Case (a) n-5-5; (b) 5-n-5; and (c) 5-5-n

- Consider Figure 3(b) to Figure 7(b). It could be concluded that adding more Man2&Man4 did not improve the productivity of the construction process. Thus, only 1 crew for each of Man2 and Man4 should be sufficient to install the scaffold.

- Consider Figure 3(c) to Figure 7(c). Unlike adding Man1, if the number of Man3&Man5 are added, the improvement in construction duration is noticeable even when the crews are small (see case 2-2-n in Figure 4(c)). This also means that the increase of Man3&Man5 has the most impact on the completion of the process.

6 CONCLUSIONS

In this study, a new application of discrete-event simulation was presented in order to facilitate an estimation of activity duration under uncertainty, enhance work productivity, and optimize resource allocation in building construction projects. The simulation system, named EZStrobe, was adopted in this study because it has been widely acknowledged as a simple, compact, and easy-to-learn tool with little effort needed for analysis. The application example of scaffolding in the building project was analyzed to illustrate the performance and capabilities of the proposed paradigm. The analysis results suggest an optimal and efficient resource allocation strategy that can be observed from the variations in total construction time to complete the process, total waiting time of workers, and total construction cost at any crew configurations.

The result from this study should prove useful to contractors in applying the concept of discrete-event simulation to facilitate the construction resource allocation. However, some further recommendations can be given to address additional research gaps and expand the capabilities of the application. For instance, more application examples can be determined to present the capabilities of the proposed approach in dealing with other types of construction projects, such as highway, railway, bridge, or dam. Similarly, more application can be performed on other types of construction activities, such as masonry works and post-tension slab installation. Moreover, due to the limitation of data collection on the construction site, the future work is proposed to gather more data on the activity duration for analyzing the duration distribution of all activities in order to accurately identify the impact of uncertainty on each construction activity.

7 ACKNOWLEDGEMENT

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