APPLICATION OF LEAN CONSTRUCTION PRINCIPLES AND SIMULATION FOR PERFORMANCE IMPROVEMENT OF EARTHWORK ACTIVITIES IN CONSTRUCTION PROJECTS ON OFFSHORE ISLANDS

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Abstract

The main objective of this study is to apply Lean Construction (LC) principles combined with a discrete event simulation tool, namely EZStrobe, to improve the performance of earthworks in construction projects on offshore islands. Based on the observation of the real-world construction process and the collection of data on each activity, a simulation model of the digging and hauling operations of coral sand is established and validated. The analysis results of the real model indicate problems of resource shortage as well as congestion in the construction process that caused delays and poor productivity. Subsequently, the three LC principles are applied to the simulation model to enhance the construction process. The analysis results from the Lean model, when are compared with the real model, show that the waiting time of construction equipment is reduced by 70.2%, the cycle and total construction time are reduced by 34.2% and 33.9%, respectively. As a result, productivity is significantly enhanced with an increase of 51.3% and a savings of 16.8% in cost. LC principles, when combined with the simulation tool, have demonstrated their effectiveness in reducing waste and improving construction processes. This approach helps managers effectively manage their plans and make informed decisions to enhance construction productivity.

Keywords: *Lean Construction; discrete event simulation; EZStrobe; performance improvement.*

1. Introduction

Earthwork is an essential activity in most construction projects on offshore islands in Vietnam. The large amount of work makes this activity mainly dependent on heavy construction equipment such as excavators, trucks and bulldozers. The geographical distance and complex maritime climate conditions in Vietnam have caused many obstacles in transporting equipment and fuel to the islands. On the other hand, the construction time is limited by the tidal water levels and the frequent breakdown of equipment also significantly affects the efficiency of the work. The above characteristics can cause significant risks to productivity, progress and cost of earthwork activities. Therefore, planning and optimizing the use of equipment fleet is very important to

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achieve productivity efficiency. In fact, this issue is often neglected due to the lack of experience in organization and management of the contractor. Furthermore, the lack of appropriate management tools has also become a barrier to analyzing and selecting optimal construction organization options. To address the aforementioned problem, this research is conducted with the goal of providing a solution to apply Lean Construction principles combined with discrete event simulation in improving productivity and minimizing waste in earthwork activities.

Lean Construction (LC) is a powerful movement in the construction industry worldwide. Essential features of LC method focus on improving processes, minimizing waste, and delivering the maximum value to the client [1]. Numerous LC techniques and tools have been developed over the past decade to manage construction projects. In practice, testing a new technique in project management can be expensive and time consuming. Currently, simulation programs are advancing rapidly, Computer modelling and simulation are performed before the actual implementation in order to reduce the risk, time, and cost involved. Modelling is a powerful tool which helps us in two important ways. The first one is revealing shortages related to designing the system and the other one is highlighting opportunities for improving the system performance. Therefore, a simulation-based approach is a suitable method for applying LC principles to enhance construction processes.

Many studies have been conducted to improve the performance of construction activities by applying LC principles using simulation. Notable examples include concrete pouring operations [1-4], reinforcement operations [5-7], brick work operations [7-9] and earthwork operations [10]. However, a review of the literature shows that the application of LC principles to improve earthwork operations is rarely studied. Subsequently, this study was conducted to fill the gap and enrich the available knowledge in the field of LC. In addition, a simulation program different from previous studies used in this study to apply LC principles is the EZStrobe simulation. This is a simulation program with many outstanding features in modeling and analyzing complex construction operations such as earthwork operations.

2. Lean Construction principles and EZStrobe simulation

2.1. Lean Construction principles

Lean Construction is an approach towards designing production systems to minimize the waste of materials and time in construction, in order to maximize benefits to customers [7]. To achieve this goal, LC is implemented through the application of various principles. In the scope of this study, three LC principles are applied and described in the following paragraphs.

Flow production in processes: The flow of processes in a lean system is defined as the movement of resources including: materials, human resources, equipment, and information within the system [11]. This principle indicates that resources interacting with activities in the system need to be circulated continuously, avoiding stagnation, so that activities can proceed without interruption. This principle impacts bottlenecks in the manufacturing system, which helps to minimize waiting time and shorten cycle time.

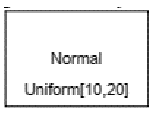
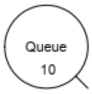
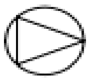
Implement the concept of pulling: Delays in material delivery are a common problem in the construction industry, causing equipment and workers to wait, which leads to reduce productivity and increase project duration. The pull principle aims to improve coordination between upstream and downstream tasks through just-in-time delivery of materials [11]. Pull describes a process in which downstream operations notify upstream operations when they are ready to begin production, and the downstream resource requirements must be provided immediately so that the process is not interrupted. On the other hand, providing the downstream's requirements earlier than needed will create unnecessary inventories and it may lead to extra cost.

Minimize non-value-adding activities: Lean thinking divides the flow activities in a process into Value-Adding (VA) and Non-Value-Adding (NVA) activities [5]. VA activities are activities that directly contribute to producing the final product and are perceived as valuable by the customer. In contrast, NVA activities are activities that consume resources, time or space but do not contribute to value creation for the product needed by the customer [9]. Examples of NVA activities include equipment repair, rework, transportation, and waiting.

2.2. EZStrobe simulation

EZStrobe is a discrete-event simulation system that uses STROBOSCOPE as its simulation tool. This program serves as a simple but powerful general-purpose simulation system, capable of modeling numerous complex construction operations. EZStrobe operates based on extended and annotated Activity Cycle Diagrams (ACDs) and was developed to function within Microsoft Visio. The basic modeling components of EZStrobe are shown in Table 1.

Table 1. Main components of the EZStrobe model [12]

Element	**Description**	**Restriction**
	A Combi represents a constrained activity. Its start will be triggered by the availability of required resources.	A Combi can only follow Queues, but be placed before any other node except a Combi.
	A Normal represents an unconstraint activity. It will start depending on 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 represents idle resources that are stored for use in a succeeding Combi.	A Queue can follow any other node other than a Queue and precede only a Combi.
	A Fork represents a probabilistic routing element that triggers a branch selection to the succeeding element.	A Fork typically follows a Combi or Normal but can also follow another Fork.
	A Draw Link represents a connectivity between different activities and queues.	-
	Release Link represents a connectivity between an activity to any other node except a Combi.	-
	Branch Link represents a connectivity between a Fork to any other node except a Combi.	-

3. A case study

The case study focuses on earthwork activities in a construction project on an offshore island in Vietnam. During this process, a total of 800,000 m³ of coral sand is excavated and transported. Table 2 provides information on the available equipment related to the task. The flow chart of the actual earthwork activities and related equipment is shown in Fig. 1.

Table 2. Details of equipment involved in earthwork activities for the project

No.	**Equipment**	**Model**	**Quantity (pcs)**	**Capacity (m^3)**
1	Excavator	XCMG - XE600DK	6	2.6
2	Truck	TONLY - TLM50	12	20
3	Bulldozer	KMS - D65PX	1	5.5

Based on direct observation of the actual construction process, the earthwork activities are organized as follows:

- The contractor organizes 6 routes for coral sand excavation, with 2 trucks arranged to transport coral sand for each route.

- Temporary roads to the excavation sites are constructed for coral sand transportation. The average transport distance is 1.2 km.

- At the dumping site, the contractor uses one bulldozer to backfill the coral sand. The bulldozer driver is responsible for guiding the trucks to the dumping location. When the volume of dumped soil is equivalent to 4 piles of coral sand, the bulldozer starts working. The trucks will wait to dump until a position is available.

- During the implementation of tasks, construction equipment often breaks down due to the construction conditions affected by the marine climate. The contractor uses one repair team to fix equipment failures.

The research process is described as follows: First, it is necessary to evaluate the actual construction process and identify the factors affecting the productivity. An evaluation method based on simulation techniques is suitable for this purpose. A simulation model that describes the actual earthwork activities is established using the EZStrobe simulation program. Model validation is performed, and the results from the model are evaluated. Next, LC principles are applied to the model, and a Lean model is formed. Finally, the results between the Lean model and the real model are compared to assess the impacts of LC principles.

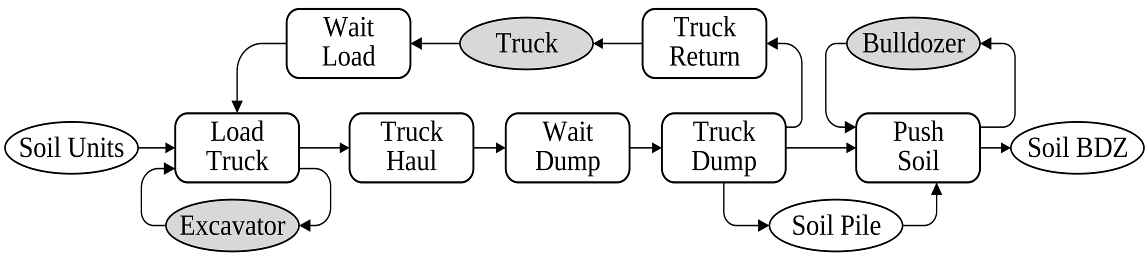


Fig. 1. The flow chart of the actual earthwork activities.

4. Real world model establishment

4.1. Collect input data for simulation

Prior to performing the simulation, it is essential to determine an appropriate time distribution for each activity. Based on time data collected from multiple observations of the same activity, the authors collected a dataset including 50 samples for the duration of each activity. Crystal Ball v11.2 software is employed to identify the distribution of time for each activity, and the Kolmogorov-Smirnov test is applied to assess the distribution of the collected data. The analysis results for each activity’s duration are presented in Table 3.

Table 3. Probability distribution of activity durations in the EZStrobe simulation model

No.	Activity name	Activity symbol	Time symbol	Duration (seconds)
1	The truck goes to load position	PreLoad	t1	Normal[31.1,6.6]
2	The excavator loads coral sand into truck	Load	t2	Normal[322.1,12.3]
3	The truck hauls coral sand to dump site	Haul	t3	Triangle[325.8,365.6,397.5]
4	The truck goes to dump position	PreDump	t4	Normal[35.6,4.7]
5	The truck dumps coral sand	Dump	t5	Normal[65.0,10.5]
6	The bulldozer pushes coral sand (20 m^3)	Push	t6	Normal[34.9,8.3]
7	The truck returns to the waiting position	Return	t7	Triangle[280.8,307.7,338.6]
8	Repair of broken excavator	Repair1	tRP1	Uniform[3579.3,5412.6]
9	Repair of broken truck while fully load	Repair2	tRP2	Uniform[2416.1,3601.1]
10	Repair of broken truck while empty load	Repair3	tRP3	Uniform[2425.9,3594.3]
11	Repair of broken bulldozer	Repair4	tRP4	Uniform[3583.1,5420.9]

4.2. Simulation model establishment and validation

The simulation model was created after collecting all the necessary input data. Figure 2 shows the simulation model of actual earthwork operations. A good simulation model should accurately reflect the actual workflow [6]. Therefore, model validation is essential after the model is established to ensure its accuracy. A popular method for model validation is to compare the simulation output with observed data from the real world, and time is the most suitable measure for comparison. Consequently, the cycle time in this study is used as a criterion to compare the similarity between the simulation and the real world. The cycle time for earthwork activities refers to the time required to complete a cycle including excavation, transportation and backfilling activities for a unit of soil. The cycle time is determined from the simulation program according to the formula shown in Table 6.

To validate the model, previous studies [5-7] have demonstrated that 10 simulation runs are sufficient. Table 4 presents the comparison results of cycle time after 10 simulation runs with the observed actual cycle time.

Table 4. Results of validation based on 10 replications of the model

Replication		1	2	3	4	5	6	7	8	9	10	Average	St. Dv.	Variation (%)
Cycle time (min)	Real word	27.2	25.9	25.9	25.4	25.7	26.4	25.8	24.2	26.4	25.8	25.9	0.8	2.5
	Simulation	25.5	25.5	25.2	25.0	25.4	25.5	24.8	25.3	24.8	24.9	25.2	0.3	

The results in Table 4 show that the difference between the simulation model and the actual data is 2.5%, which is less than 5%, and therefore acceptable. Thus, the simulation model has been validated, qualified to analyze and evaluate the actual earthwork activities. The analysis results from the real model are summarized in Table 5.

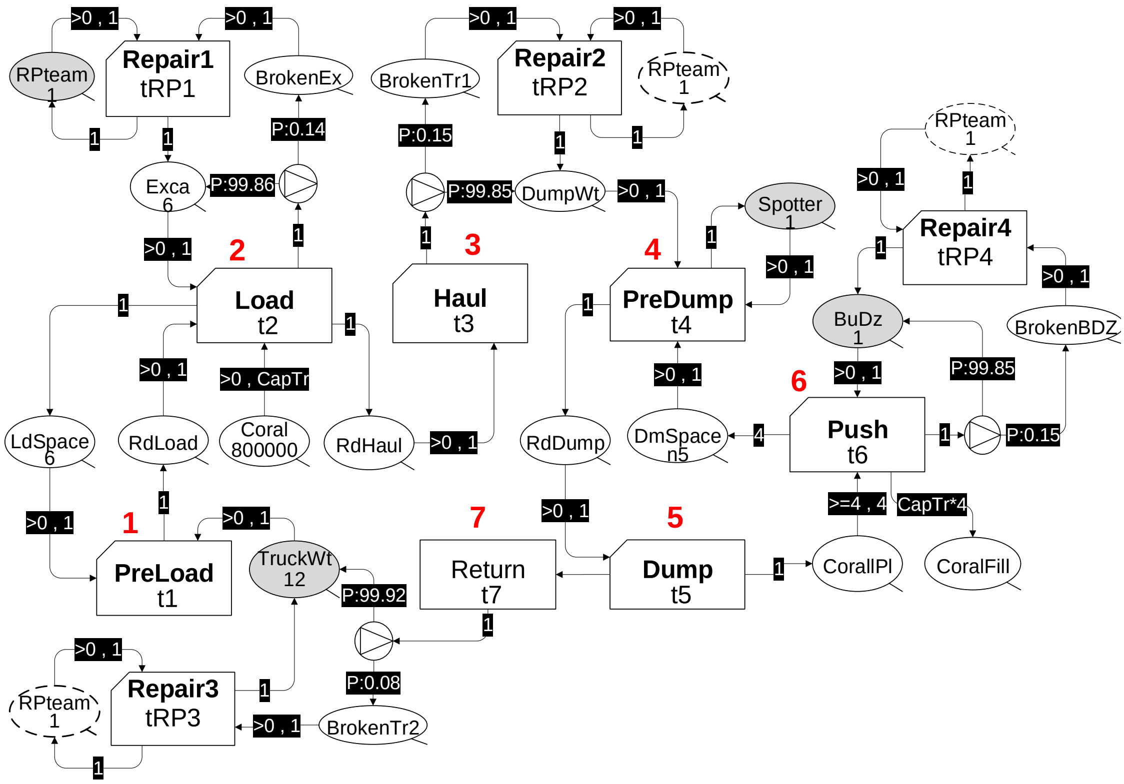


Fig. 2. Real model of earthwork activities in the project.

Table 5. The analysis results from the real model

Time (hr)	**Productivity (m^3/hr)**	**Cycle time (min)**	**Excavator wait time (min)**	**Truck wait time (min)**	**Bulldozer wait time (min)**	**Excavator utilization (%)**	**Truck utilization (%)**
1129.34	708.39	25.19	4.02	0.77	4.33	60	96

From the results in Table 5, it can be seen that the excavator and bulldozer have large waiting times of 4.02 and 4.33 minutes, respectively. The total waiting time for equipment accounts for 36.2% of the cycle time. In addition, the excavator's utilization rate is low at 60%, which is the cause of reduced productivity and increased construction time. Subsequently, LC principles are applied to reduce waste, as presented specifically in the next section.

5. Applying Lean principles to improve model

Flow production in processes: Based on the actual observation at the dumping area, the contractor did not arrange a spotter to guide the trucks to the dumping location. As a result, the bulldozer driver had to spend time doing that, which leads to waiting time for both the bulldozer and the trucks. Applying the principle of flow production in processes to reduce congestion at the dumping area. The first, arrange 2 spotters to guide the trucks to the dumping location, and the bulldozer will work immediately whenever there is a pile of soil, eliminating unnecessary awaiting. On the other hand, increase the number of bulldozers to 2 so that the filling is completed quickly, ensuring that trucks have a continuous dumping location.

Implement the concept of pulling: At the excavation site, soil is loaded by excavators and transported to the dump area by trucks. The number of trucks is an important factor in providing resources for the operations of excavators and bulldozers. The analysis results from the actual model show that the excavator has a significant waiting time of 4.02 minutes per cycle, which leads to waste and low productivity. Consequently, the pull principle is applied by increasing the number of trucks to provide resources in time for the operations of excavators and bulldozers. Through simulation, an optimal number of trucks is selected, balancing time efficiency and cost considerations.

Minimize non-value-added activities: Equipment breakdowns are a common issue in construction projects on offshore islands, significantly affecting construction progress and productivity. According to the value stream principle, repair activities are non-value-added activities and need to be minimized. In fact, equipment repair has not been interested in by contractor. Using only 1 repair team has proven insufficient to promptly address issues when multiple pieces of equipment break down. Subsequently, in the Lean model, the number of repair teams is increased to 2 to ensure timely repairs. In addition, to reduce the rate of equipment breakdowns, the following measures need to be implemented in practice.

1) Regularly check equipment and periodic maintenance;

2) Repair temporary roads to minimize rough surfaces and facilitate smoother truck transportation;

3) Always have necessary replacement materials available when equipment is seriously damaged.

After identifying and applying the Lean principles to the actual model, a new Lean model including all improvements is established, as illustrated in Fig. 3.

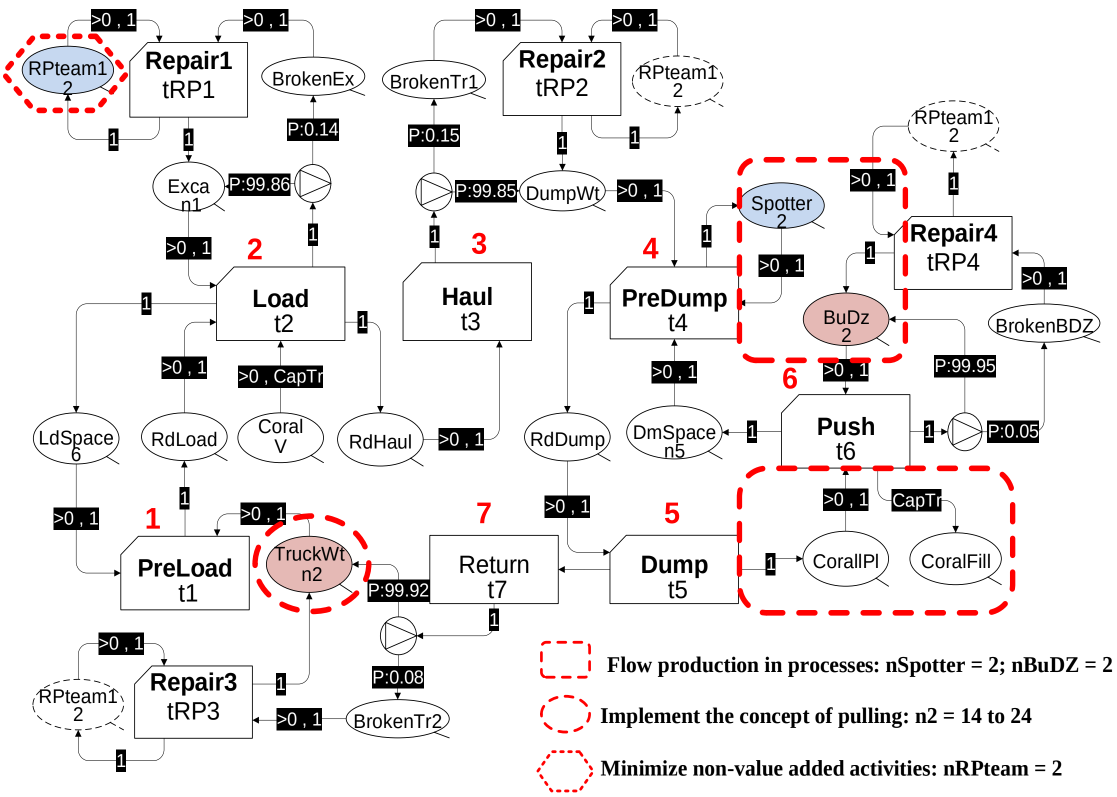


Fig. 3. Lean simulation model of the earthwork activities.

6. Comparison between the Lean model and the real model

To evaluate the effectiveness of LC principles after applying them to the real model, the output results of the Lean model and the real model are compared. The comparison criteria include total construction time, cycle time, construction productivity, total cost, waiting time, and equipment utilization efficiency. Table 6 depicts the output parameter of the simulation results.

In the Lean model, scenarios using varying numbers of trucks from 14 to 24 are analyzed to identify the most optimal configuration. The results of the scenario analysis are summarized in Table 7.

The comparison of scenarios in Table 7 shows that, using 18 trucks to transport soil in the Lean model provides the best balance. Considering many criteria in general, although scenario 3 does not achieve the highest productivity, it is an effective option in terms of equipment utilization and waste reduction by minimizing equipment waiting time. In addition, this scenario has the lowest cost, which is a key criterion that contractors are always interested in. To evaluate the impacts of the most optimal Lean model, a comparison was conducted between the analysis results of the actual model and the Lean model. The comparison results are illustrated in the chart as shown in Fig. 4.

Table 6. The output parameter of the simulation results

Result	Description of results	Declaration formula in simulation
Time	Total construction time (hr)	SimTime/(60*60)
Productivity	Construction productivity (m^3/hr)	V/Time
CycleTime	Cycle time for digging and hauling a unit of soil (min)	(Exca.AveWait+t2+t3+DumpWt.AveWait+t4+t5+BuDz.AveWait+t6)/60
LC	Larbor Cost (million VND)	(G1*n1+G2*n2+G3*n3+G4*n4+G5*n5)*Time
EC	Equipment cost (million VND)	(G6*n1+G7*n2+G8*n3)*Time
Cost	Total cost (million VND)	LC+EC
ExcWt	Excavator wait time (min)	Exca.AveWait/60
TrkWt	Truck wait time (min)	(TruckWt.AveWait+DumpWt.AveWait)/60
BuDzWt	Bulldozer wait time (min)	BuDz.AveWait/60
ExcUt	Excavator utilization	1-(Exca.AveCount)/n1
TrkUt	Truck utilization	1-(TruckWt.AveCount+DumpWt.AveCount)/n2
BuDzUt	Bulldozer utilization	1-(BuDz.AveCount)/n3
* *Note:* SimTime - the simulation run time in seconds; V = 800000 m^3 - volume of soil; Queue.AveWait - the average waiting time for resources in queue; Queue.AveCount - the time-weighted average of queue content; t2, t3, t4, t5, t6 - the times of loading, moving, waiting for dumping, dumping, and bulldozing activities described in Table 3; n1, n2, n3, n4, n5 - the number of excavators, trucks, bulldozers, repair teams and spotters; G1 = 0.0875, G2 = 0.0625, G3 = 0.0625, G4 = 0.125, G5 = 0.05 - hourly labor costs for excavator drivers, truck drivers, bulldozer drivers, repair workers, and spotters, respectively, unit (million VND/hour); G6 = 0.75; G7 = 0.3; G8 = 0.5 - hourly equipment costs for excavators, trucks, and bulldozers, respectively, unit (million VND/hour).		

Table 7. Summary of the analysis results of simulation scenarios in both the Lean model and the real model based on the number of trucks

Scen-arios	Number of trucks	Time (hr)	Productivity (m^3/hr)	Cycle Time (min)	ExcWt (min)	TrkWt (min)	BuDZWt (min)	ExcUt (%)	TrkUt (%)	Cost (Million VND)	Wait time (min)
Real	12	1129.34	708.39	25.19	4.02	0.77	4.33	60	96	12126.24	9.11
1	14	933.27	857.21	18.79	2.26	0.04	2.18	73	99	11269.18	4.48
2	16	820.23	975.34	17.44	1.24	0.10	1.84	83	99	10498.96	3.18
3	**18**	**745.57**	**1073.00**	**16.54**	**0.57**	**0.52**	**1.62**	**92**	**97**	**10083.90**	**2.70**
4	20	736.27	1086.56	16.44	0.49	2.47	1.59	93	89	10491.85	4.55
5	22	736.24	1086.60	16.45	0.49	4.68	1.59	93	81	11025.25	6.75
6	24	736.17	1086.70	16.41	0.48	6.88	1.59	93	74	11557.91	8.96

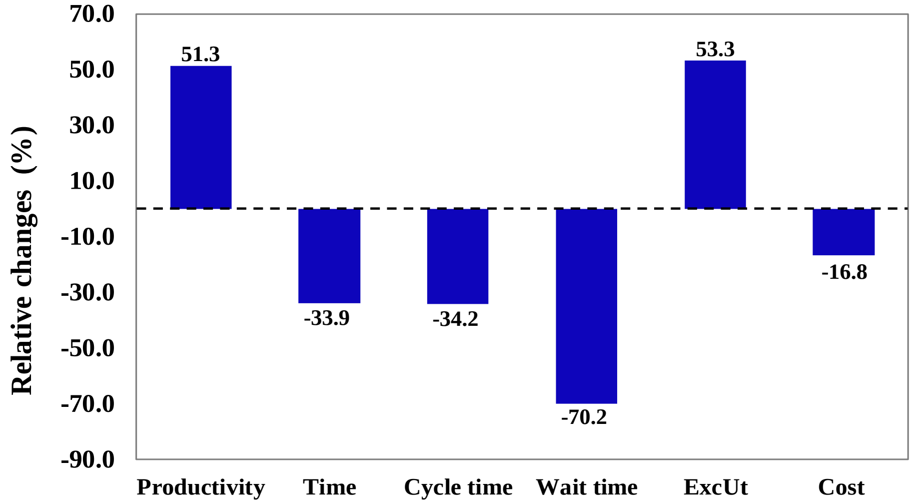


Fig. 4. Relative changes in terms of time, productivity, cost, cycle time, wait time between the Lean model and the real model.

From the results in Table 7 and Fig. 4, it can be seen that the Lean model reflects positive impacts in improving the efficiency of the actual earthwork activities. Specifically, it reduces the waiting time of construction equipment by 70.2%, from 9.11 minutes to just 2.7 minutes. The cycle time is shortened to just 16.54 minutes. As a result, the total construction time decreases by 33.9%, to 745.57 hours, and the construction productivity increases by 51.3% from 708.4 m^3/hour to 1073 m^3/hour. In addition, equipment utilization in the Lean model is significantly improved, reaching 92% for excavators and 97% for trucks. Moreover, increasing the number of equipment appropriately in the Lean model saves the project cost by 16.8%. This result has alleviated concerns about going over budget when applying Lean principles to enhance performance.

7. Conclusion

In this study, by utilizing the capabilities of the EZStrobe simulation program, three LC principles including flow production in processes, implementing the concept of pulling, and minimizing non-value-added activities, are applied to the real model to effectively enhance the performance of the earthwork construction process. The shortcomings of the real model are identified and addressed, yielding expected outcomes such as reducing the waiting time of equipment by 70.2%, increasing the construction productivity by 51.3%, and reducing the construction costs by 16.8%. The results of the study confirmed the great potential of LC principles in improving construction processes and reducing waste. Although the construction industry witnesses a large amount of waste in its processes, effective measures to reduce them are rarely taken. LC principles are applied may yield different results depending on the characteristics of the construction process. Based on a comprehensive investigation of construction activities, managers can apply LC principles most effectively. Furthermore, changes or modifications in the construction operations may have to be made in order to better apply these principles. However, the costs of these modifications will always be considerably less than the benefits made by LC principles.

This study has demonstrated a comprehensive process for applying LC principles through the EZStrobe simulation program to analyze construction activities. In addition, the practicality of the simulation model is verified by model validation to increase the reliability for the analysis results from the model. The content and results of this study aim to guide and persuade contractors to apply LC principles to enhance construction processes, eliminate waste, and boost profitability.

Finally, it should be concluded that while this study is just dedicated to one of the many operations in a construction project, it can be predicted that they have a high potential for improvement through the application of Lean principles and simulation. Future work can expand this study to cover other processes in the construction industry.

Acknowledgement

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ỨNG DỤNG NGUYÊN TẮC XÂY DỰNG TINH GỌN VÀ MÔ PHỎNG ĐỂ CẢI THIỆN HIỆU SUẤT HOẠT ĐỘNG THI CÔNG ĐẤT TRONG DỰ ÁN XÂY DỰNG TRÊN ĐẢO XA BỜ

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Tóm tắt: Mục tiêu chính của nghiên cứu này là áp dụng nguyên tắc xây dựng tinh gọn kết hợp với mô phỏng sự kiện rời rạc cụ thể là EZStrobe, để cải thiện hiệu suất của các hoạt động đào đắp trong một dự án xây dựng trên đảo xa bờ. Dựa trên việc quan sát quá trình thi công thực tế và thu thập dữ liệu của từng hoạt động, một mô hình mô phỏng hoạt động đào và vận chuyển cát san hô được thiết lập và xác thực. Kết quả phân tích từ mô hình thực tế đã chỉ ra các vấn đề về thiếu hụt tài nguyên cũng như sự tắc nghẽn trong quá trình thi công, gây ra tình trạng chậm tiến độ và năng suất kém. Từ đó, ba nguyên tắc xây dựng tinh gọn đã được áp dụng vào mô hình mô phỏng để cải tiến quá trình thi công. Kết quả phân tích từ mô hình tinh gọn được so sánh với mô hình thực tế cho thấy, thời gian chờ của các thiết bị xây dựng giảm 70,2%, thời gian chu kỳ và tổng thời gian xây dựng giảm lần lượt 34,2% và 33,9%. Kết quả này dẫn đến năng suất được cải thiện đáng kể với mức tăng 51,3% và tiết kiệm 16,8% chi phí. Các nguyên tắc xây dựng tinh gọn khi kết hợp với công cụ mô phỏng đã chứng minh được tính hiệu quả trong việc loại bỏ các lãng phí và cải thiện quy trình thi công. Nó giúp các nhà quản lý có thể quản lý hiệu quả các kế hoạch của mình và đưa ra quyết định sáng suốt để nâng cao năng suất xây dựng.

Từ khóa: *Xây dựng tinh gọn; mô phỏng sự kiện rời rạc; EZStrobe; cải thiện hiệu suất.*

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