Resource Utilization and Repetitive Construction Scheduling using the Discrete Event Simulation Method

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ABSTRACT

The efficient utilization of resources in repetitive construction projects is crucial to optimizing schedules and reducing costs. This study investigates the application of Discrete Event Simulation (DES) to enhance resource utilization in scheduling repetitive construction activities, specifically the construction of Type-36 houses in Palu City, Indonesia. Traditional project-based planning methods, such as the Critical Path Method (CPM), are compared with production-based planning approaches. The study shows that although CPM can effectively determine project completion times, it falls short in optimizing resource allocation, particularly in scenarios involving repetitive tasks. By employing the DES tool SIMUL8, the study models the construction process and simulates various resource allocation scenarios to identify the optimal resources required. The results indicate that DES provides a more dynamic and accurate analysis, allowing real-time adjustments and improved resource management. The study concludes that integrating DES into construction project management can significantly enhance efficiency, reduce project duration, and optimize resource utilization.

Keywords-project management; production management; construction management; discrete event simulation; critical path method; repetitive construction

I. INTRODUCTION

Large-scale house construction can be considered a construction industry sector that closely resembles the manufacturing industry. This similarity arises because houses of similar models and sizes are often built repetitively within a confined area, utilizing specialized worker teams for each construction phase [1]. As a result, the construction of many houses can be regarded as a manufacturing process, where planning and control techniques can adopt production management methods commonly used in the manufacturing sector.

Planning and control methods frequently employed in construction projects are activity-based, also called project-based planning and control methods or project management [2-4]. An example is the Critical Path Method (CPM). In these activity-based methods, the duration of each task depends on the quantity of work and the production rate of the resources utilized [5], as shown in (1).

$$activity\ duration = \frac{work\ quantity}{production\ rate} \quad (1)$$

The project's completion time is determined by adding up the durations of all its critical activities. Thus, the overall completion time can only be altered if the durations of the critical activities change [6].

The manufacturing industry's prevalent planning and control methods are production-based, also called production management [7-13]. In this approach, Cycle Time (CT) is determined by the Work In Process (WIP) and Throughput (TH) [14-16] as expressed in:

$$CT = \frac{WIP}{TH} \quad (2)$$

TH is the output from the production system per unit time, WIP is the number of products being processed in the production system, and CT is the time required to complete a product [17], which forms the basis of queuing theory using (3), which is also known as Little's Law [14, 15, 18, 19].

$$L = \lambda W \quad (3)$$

where L is the average number of items in the system (items), λ is the average arrival rate of items to the system (items/unit time), and W is the average wait in the system (time units/item).

Production-based planning and control methods consider that the completion time of a project can also be influenced by the number of units waiting to be completed within a production system (WIP). In contrast, project-based planning and control methods do not consider this WIP parameter. If building many houses is to be considered a manufacturing process, then the WIP parameter must be considered. If WIP is considered, it becomes crucial to analyze the utilization of human resources or work groups engaged in multiple activities, a common scenario in construction projects. Poor management of these resources can lead to bottlenecks in the production system. Traditional project-based planning and control methods such as CPM do not account for the human resources required for each activity [20, 21]. Instead, CPM focuses solely on the duration and dependency logic between activities within a construction project. Using project-based planning and control methods such as CPM to analyze human resource utilization in repetitive construction projects is impractical. For example, if 100 similar constructions are to be built, 100 separate CPM networks would be required to analyze human resource utilization effectively. Therefore, project-based planning and control methods are less effective for repetitive construction projects, such as building multiple houses.

In [22], simplified scheduling involved Discrete Event Simulation (DES). However, this study did not explore the intricate dynamics of resource bottlenecks or human resource utilization across similar tasks, which are common in repetitive construction projects. In [23], modular construction was studied that involved pre-fabricated units assembled on site. Although this work provides insights into logistics, weather impacts, and human resources utilization, it does not address challenges unique to repetitive on-site construction of similar units, such as houses. In [24], the impact of variability on construction processes was highlighted, and strategies like modularization and prefabrication were proposed to mitigate variability. However, this study did not provide detailed insights into dynamic resource allocation for repetitive on-site tasks. This study proposes a viable alternative for planning and managing repetitive construction projects utilizing production-based planning methods by providing a detailed resource allocation framework tailored to repetitive residential construction using a DES package called SIMUL8.

II. METHODOLOGY

A. Data

The research was carried out at a residential construction site in a low-income community in Palu City, Central Sulawesi, Indonesia. The houses, referred to as Type-36, have a unit size of 36 m^2. The study used the purposive sampling technique, specifically the typical case sampling variant. Purposive sampling is a non-random sampling technique in which the researcher determines what data to obtain and selects the entities that can provide it [25]. Table I shows information on typical construction activities for these standard Type-36 houses gathered through on-site observations and interviews with site engineers from the housing developer.

TABLE I. HOUSE TYPE-36 CONSTRUCTION ACTIVITY AND DURATION

Activity code	Preceding activity	Activity name	Duration (days)	Resource
A	-	Site clearance	2	Mason
B	A	Stake out	2	Mason
C	B	Foundation excavation	2	Mason
D	C	Plumbing pipes installation	1	Mason
E	C	Foundation	2	Mason
F	C	Steel fabrication	3	Mason
G	E, F	Plinth beam	2	Mason
H	D, G	Foundation backfills	2	Mason
I	H	Wall, column, window, and door frame	7	Mason
J	I	Tie beam	2	Mason
K	J	Brick rafter	3	Mason
L	K	Steel roof	2	Roofer
M	L	Electrical rough-in	2	Mason
N	M	Wall plaster	10	Mason
O	N	Floor	4	Mason
P	O	Bathroom and toilet	2	Mason
Q	P	Septic tank	2	Mason
R	Q	Carport	2	Mason
S	R	Ceiling	3	Roofer
T	S	Doors and windows installation	3	Door and window installer
U	T	Painting	4	Painter
V	U	Electrical fitting	2	Electrical fitter
W	V	Water tank	1	Plumber
X	W	Cleaning	2	Cleaner

B. CPM Network

An arrow diagram was employed to construct the CPM network and calculate the project completion time using the activity durations and the immediately preceding activities provided in Table I. The forward pass, backward pass, and total float calculations used (4), (5), and (6) respectively.

$$EET_j = \max(EET_i) + Duration_{ij} \quad (4)$$

$$LET_i = \min(LET_j) + Duration_{ij} \quad (5)$$

$$TF_{ij} = LET_j - Duration_{ij} - EET_i \quad (6)$$

EET is the earliest event time, LET is the latest event time, and TF is the total float, as shown in Figure 1.

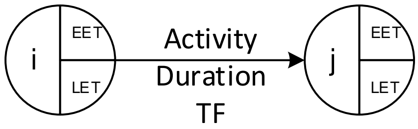

Fig. 1. CPM notation.

Figure 2 shows the CPM network and calculations, which determined that the project completion time for one house was 65 days. The critical path is shown in the red-colored arrows.

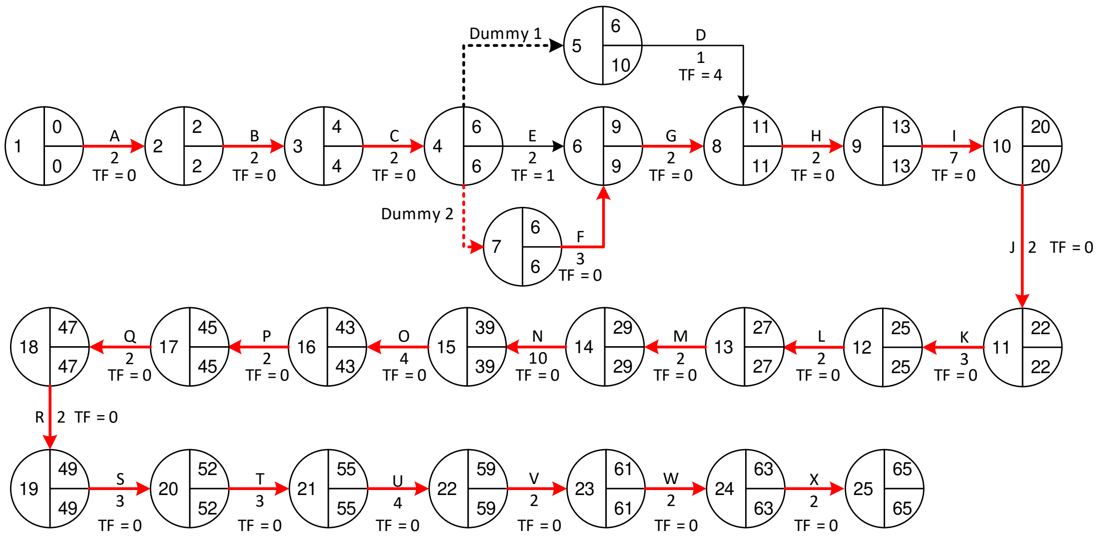

Fig. 2. CPM network calculations.

C. DES/SIMUL8 Network

The activity durations and the immediately preceding activities provided in Table I were used to create a network in the SIMUL8 simulation package, as shown in Figure 3. SIMUL8 is a DES package based on queueing theory. Queuing theory offers mathematical models for examining waiting line dynamics. Meanwhile, DES employs these models to replicate and assess the operational behavior of intricate systems across temporal dimensions, thereby augmenting the decision-making process [23, 24].

DES models systems by simulating their operations as a series of individual events occurring over time. Each event signifies a change in the system's state at a particular moment [26]. DES is especially useful for examining complex systems where interactions and changes happen at distinct intervals, making it well-suited for analyzing repetitive construction processes. In the SIMUL8 model, activities A through K, which use the same type of resources, i.e., masons, were grouped into an activity called Masonry_1, while activities M through R, which also use masons, were grouped into an activity called Masonry_2. SIMUL8 elements [27, 28] in Figure 3 are explained in Table II.

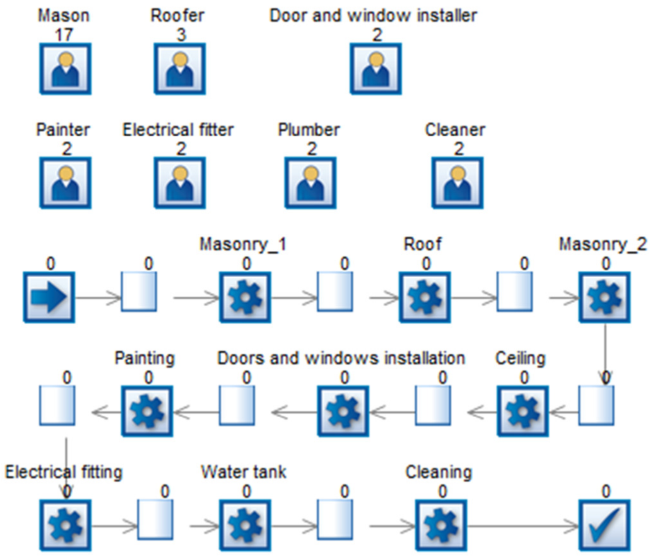

Fig. 3. SIMUL8 DES model.

TABLE II. SIMUL8 ELEMENTS

Element name and icon	Description
Work Item	A Work Item is the work done in the simulated system, such as factory products and house units to be built.
Start Point 	Start Point is an element that facilitates creating or generating Work Items within the simulation model. They generally represent the initial stage of a process or subprocess at which moving entities ingress into the simulation. Users possess the capability to determine the frequency at which Work items are introduced at this juncture. Work entry points are dynamic entities as they push work into the model.
Queue 	Queue is an element wherein Work items may be systematically arranged in sequence. They function as intermediaries or repositories between various stages of a procedure.
Activity 	Activities represent the element in which Work items undergo processing. Typically, a particular duration is allocated to execute the task, and occasionally, this necessitates utilizing one or multiple resources.
End 	The End element provides a means for Work items to leave the simulation model. SIMUL8 records overall and summary Work item process statistics at these points.
Resource 	Resources are items in the model that Activities can be set to require before Work items can be processed. Therefore, they can be staff or special tools. Activities requiring a Resource cannot begin work until both a Work item and the specified Resource are available. Resources can also be shared between multiple Activities, favoring Activities with the highest Priority setting.

To ensure that the SIMUL8 network model works as intended, the completion time of one house in SIMUL8 must match the 65-day completion time of one house in CPM, verified in Figure 4.

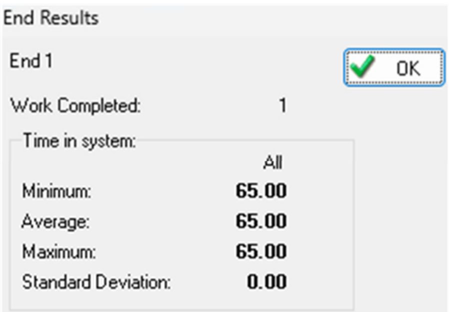

Fig. 4. Completion time of one house in SIMUL8.

III. RESULTS AND DISCUSSION

As the simulation result for completing one house is 65 days, the same as the completion time calculated by CPM, the simulation model is verified and works as intended. It should be noted that since the simulation result in Figure 4 was based on the assumption that only one house was completed, resources were always available for each activity, and resources were not shared between activities, which is not always the case in real-world situations where house developers typically build multiple houses in one location. For example, a mason typically works on more than one activity, as shown in Table III.

TABLE III. RESOURCES AND ACTIVITIES

No.	Resource name	Activity name
1	Mason	Site clearance, stake out, foundation excavation, foundation, plumbing pipes installation, foundation backfills, steel fabrication, plinth beam, wall, column, window, and door frame, tie beam, brick rafter, electrical rough-in, wall plaster, floor, bathroom and toilet, septic tank, and carport.
2	Roofer	Steel roof and ceiling
3	Door and window installer	Doors and windows installation.
4	Plumber	Water tank
5	Electrical fitter	Electrical fitting
6	Painter	Painting
7	Cleaner	Cleaning

Table III shows that the masons performed most of the work, a common practice in the construction of Type-36 houses in Palu, Indonesia. A typical house developer in Palu builds up to 100 Type-36 houses in one year. The inter-arrival times must be determined to simulate the construction of 100 houses in SIMUL8. The inter-arrival time is the time between the arrival of each new work item into the system. Based on the collected data, the inter-arrival time at the selected house construction location ranges from one to 15 days.

The SIMUL8 network in Figure 3 was simulated 300 times with the following scenarios: the number of available masons was set between one and twenty groups and shared between activities Masonry_1 and Masonry_2, roofer availability was fixed at three groups and shared between activities Roof and Ceiling. At the same time, all other resources were kept constant in two groups and not shared. The assumptions used in the simulation parameters are as follows:

- Resource skills are assumed to be at the same level.
- Activity duration is deterministic.

Table IV presents selected results from the simulation of 300 scenarios, focusing on scenarios where each house was completed in 65 days. It highlights the effects of varying inter-arrival times and the number of masons on their utilization and overall project duration.

TABLE IV. SIMULATION RESULTS

Scenario no.	Inter-arrival time (days)	No. of mason group	Mason utilization (%)	Individual house completion time (days)	Project duration (days)
1	13	4	22.60	65	1365
2	10	5	18.08	65	1065
3	9	6	15.06	65	965
4	7	7	12.91	65	765
5	6	9	10.04	65	665
6	5	10	9.04	65	565
7	4	13	6.95	65	465
8	3	17	5.32	65	365

Inter-arrival time (days) refers to the time between the arrivals of house order, measured in days. No. of mason group indicates the number of masons working together. Masons' utilization is the percentage of time the masons are actively working on tasks. Lower values suggest that the masons spend more time waiting for new tasks. Individual house completion time is the time needed to complete one house. Project duration is the total duration to complete 100 houses, measured in days. Shorter project durations suggest that the project is completed more quickly.

A. Analysis of Simulation Results

1) House Completion Time

The house completion time remains constant at 65 days across all scenarios in Table IV, indicating that each house takes 65 days to complete regardless of the number of masons and their respective inter-arrival times.

2) Mason Utilization

Mason utilization increases as their number decreases. For instance, for 17 masons, the utilization is 5.32%, and for four masons, it increases to 22.60%. This means that with fewer masons, each mason works more intensively (higher utilization rate).

3) Project Duration

The project's total duration increases as the number of masons decreases and their inter-arrival time increases. For instance, with 17 masons, the project takes 365 days, whereas, with four masons, it extends to 1365 days. This highlights a direct correlation between the number of available masons and the total project duration.

B. Sensitivity Analysis

Sensitivity analysis examines how changes in a model's input impact its outputs, helping validate the model and identify key parameters contributing to simulation uncertainty [29]. Scenario 8 in Table IV was arbitrarily chosen for a sensitivity analysis using three types of variables: independent, dependent, and controlled. The independent variable is the one that the researchers intentionally changed in the simulation. The dependent variable is the one that researchers observe or measure. The controlled variable was kept constant throughout the experiment. Table V presents the utilization of these three types of variables in the sensitivity analysis. The sensitivity analysis results are presented in Figures 5 and 6.

TABLE V. TYPES OF VARIABLES USED IN THE SENSITIVITY ANALYSIS

Variable type	Variable name	Remarks
Independent variable	No. of mason group	Ranging from 1 to 20 groups of mason
Dependent variable	Individual house completion time (CT), mason utilization, and project duration	Observed
Controlled variable	Inter-arrival time, the number of other resources, and the number of houses.	The inter-arrival time was constant at three days, the number of roofers was constant at three groups, the number of other worker groups was kept constant at two, and the number of houses was constant at 100.

Figure 5 shows that at 3-day inter-arrival times, adding more mason groups decreases CT, WIP, and project duration until the optimum number of 17 mason groups is reached, after which increasing the number of masons to 18, 19, or 20 does not change the average CT or project duration. Figure 6 shows that at 3-day inter-arrival times, adding more mason groups decreases CT and project duration until the optimum number of 17 mason groups is reached, after which increasing the number of masons to 18, 19, or 20 does not change the average CT or project duration but decreases mason utilization. Figure 6 also shows that if the house developer's priority is to maximize mason utilization, they need to decrease the number of masons, but at the cost of longer CT and project duration.

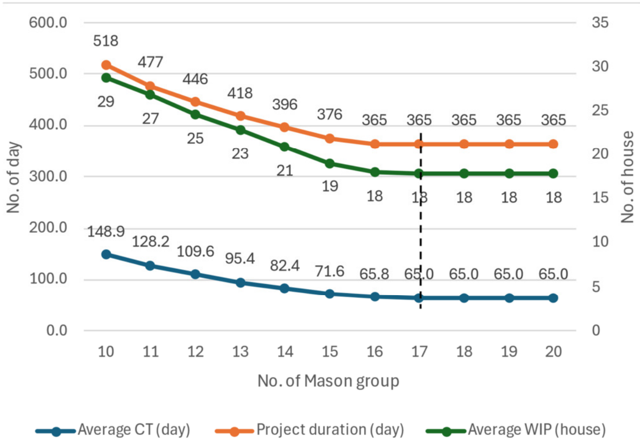

Fig. 5. WIP, CT, and project duration sensitivity analysis.

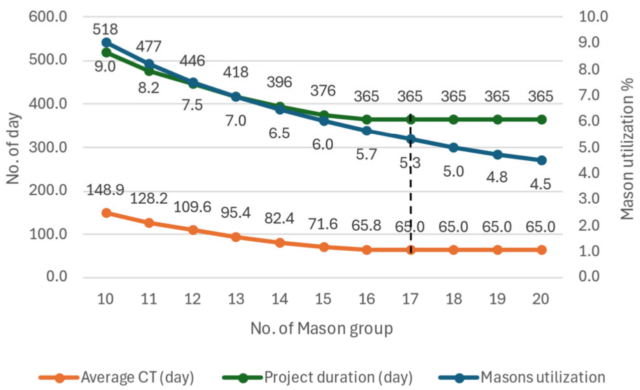

Fig. 6. CT, project duration, and masons utilization sensitivity analysis.

C. Project Management

To minimize project duration, increasing the number of masons is effective. However, this must be balanced with the cost and availability of masons. Constant house completion time suggests a fixed workload per house, so strategic planning around the number of available masons can significantly impact overall efficiency. Moreover, timely house construction time benefits buyers and developers for several reasons, as explained in the following.

1) Buyer's Benefits

From a financial planning point of view, buyers usually arrange their mortgages and bank loans based on their house's expected completion time. In addition, many buyers plan to move out of their current rental house only when their new house is ready. If their house completion is delayed, they may have to extend their rent or move to a temporary home, causing unexpected costs. Second, from a personal planning perspective, buyers must prepare their move, which involves coordination with movers, taking a day off work, and managing logistics. Known house completion time allows buyers to plan efficiently. Third, from a psychological and emotional point of view, a timely completion time provides buyers with peace of mind.

2) Developer's Benefits

From a cost management point of view, delayed house completion incurs more labor costs. House developers need to pay workers for a longer period, which increases the project's overall costs. Second, from an operational efficiency perspective, an efficient project schedule enhances planning and resource allocation, such as labor, equipment, and materials allocation. Third, from a financing point of view, house developers often fund their projects through bank loans. The longer the construction time, the more interest they have to pay, increasing the overall financial obligation. Fourth, from the perspective of market conditions, real estate markets can be unpredictable. The completion of a house in time gives developers opportunities to sell or lease properties while market conditions are good. Moreover, consistently completing projects on time strengthens a developer's reputation for reliability, attracting more investors and clients in the future.

IV. CONCLUSION

This study demonstrated the benefits of using production-based planning by utilizing DES in optimizing scheduling and resource utilization in repetitive construction projects, specifically in the context of building Type-36 houses in Palu City, Central Sulawesi, Indonesia. The study also highlights the limitations of CPM in addressing the dynamics and complexities of repetitive construction tasks. The DES model, built using SIMUL8, provides a more dynamic and detailed analysis of the repetitive construction process, allowing real-time adjustments and optimization that are not feasible with static methods such as CPM. Furthermore, the study provides a foundation for future research on production-based scheduling and resource management in repetitive construction projects.

A. Limitations

1) Dependence on Accurate Input Data

Accurate and complete data input is crucial for the DES model's reliability. Errors in data, such as inaccurate interarrival times, task durations, and resource availability, can produce misleading results. This dependency creates a significant challenge for real-world situations, where collecting accurate data is often resource-intensive and complex.

2) Exclusion of Non-Quantifiable Factors

The study focuses primarily on quantitative metrics, such as task durations, resource utilization, and project schedules. However, it does not consider non-quantifiable factors that can significantly impact construction projects, such as weather conditions and worker skill levels.

3) Assumption of Constant Resource Availability

The DES model in this study assumes that resources such as masons and roofers are readily available throughout the project. Meanwhile, labor availability often fluctuates in real-world situations due to competing projects and absenteeism.

4) Static Assumption of Task Durations

The DES model in this study assumes that the duration of the activities remains constant throughout the project. However, due to efficiency improvements and learning effects, activity durations may be shorter over time. On the other hand, inefficiencies or delays in earlier stages may prolong the duration of subsequent stages.

B. Suggestions for Future Research

Future studies could consider dynamic variables and qualitative factors in the DES model using real-world constraints, such as worker skill levels, weather conditions, and fluctuating resource availability, to enhance its practical applicability.

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