Managing Trade-off Between Cost and Time in Project Scheduling Problems Using Discrete Event Simulation

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Abstract: Project Management is a key activity in engineering and business entities to achieve specific objectives (e.g., construction, expansion, supply chain, and replacement). Effective project management includes a detailed investigation of the project's costs and benefits and examining the short- and long-term effects of project design and implementation. In the mining industry, due to the operations' inherent complexity and uncertainty associated with geological and financial inaccuracies, there is a substantial risk that the project may run over budget and schedule. It is vital to consider the project's uncertainties to meet the project's goals. This paper proposes a combined simulation and optimization model for time-cost trade-off project scheduling problems under uncertainty. A numerical example is conducted to demonstrate the effectiveness of the developed model through an electrical substation construction project conducted in a mine. By introducing numerous crashing scenarios to quantify the impact of uncertainty on the entire project and to assess the risks, the trade-off between time and cost is achieved under the project budget and deadline constraints. The proposed research has a significant potential to improve the management of construction projects considering a detailed project management methodology.

1 INTRODUCTION

Project implementation has three dimensions: (1) completing the project in a possible earliest time, (2) minimizing the cost through minimizing resource usage, and (3) providing a high-quality, safe, and environmentally friendly project outcomes. This indicates when scheduling a project, there are inevitable trade-offs that must be dealt with. This paper seeks a balance between cost and completion time. It should be noted that environmental and safety issues cannot be balanced because they are the uppermost priorities for a project. The first dimension involves the decisions and questions regarding the project completion time, project bottlenecks, and what can be done to prevent the project from being delayed. The second dimension addresses the resources that need to be used such that the project is accomplished within the budgeted cost, while at the same time not delaying the project completion time. The third dimension refers to scope which is difficult to quantify. The project must provide all the requirements included in the project scope such as quality, safety, environmental concerns, sustainability, or any other performance measurements (Hickson and Owen, 2015). Large-scale engineering projects such as mine development call for the efficient coordination of numerous operations carried out by several organisational units. These projects should be handled carefully to avoid interrupting the turnover of project length while avoiding capital overruns because they are inherently complicated and uncertain due to the influence of internal and external factors. Since the value of mining projects is sensitive to time and cost, the time and cost management of a construction project is of vital importance. Project planning problems investigating the trade-off between cost and time of the project is called time-cost trade-off (TCT) problems in the literature.

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2 LITERATURE REVIEW

In this regard, Xu et al. (2018) developed an integrated dynamic approach for analyzing the project schedule risk by combining discrete event simulation (DES) with system dynamics. The developed model is applied to a bridge construction project to reveal the effect of risk factors on the schedule. Romanskaya and Berdnikov (2020) proposed an integrated methodology for schedule risk management, combining the The Project Evaluation and Review Technique (PERT) with the decision tree method. Acebes et al. (2021) proposed a new metric to measure the impact of each activity on the total project risk while it is underway. The probability factor is evaluated by Monte Carlo simulation, while the impact factor is built on the schedule risk baseline concept. Song, Martens, and Vanhoucke (2022) aimed to measure and evaluate if the project progress is acceptable for resource-constrained projects considering project delays and resource restrictions by applying schedule risk analysis. Chen, Lu, and Han (2022) investigated the interdependency between the sequence of risk occurrence for construction schedule under uncertainty by the Bayesian-driven Monte Carlo approach. Mostafaei et al. (2022) examined a granite mine project to carry out a financial analysis for the exploitation duration. Defining the sale price and annual production is uncertain, two net present value (NPV) models were generated utilizing Monte Carlo simulation and Support Vector Machine (SVM).

In addition, the time-cost trade-off problems have been studied by various simulation techniques in the field of project management. Simulation is a powerful tool for modelling complex problems and its ability to accurately reflect the structure of the real world (Hillier and Lieberman, 2010). To optimise the time-cost trade-off scheduling problem considering the stochastic character of the project network, Feng, Liu, and Burns (2000) suggested a hybrid technique including genetic algorithms with simulation methods. A DES methodology was developed by Li and Lei (2010) to analyse the time-cost trade-off in uncertain construction scheduling problems. To calculate the critical path and the project duration under uncertainty, Jolai et al. (2013) researched a project network problem. A numerical example was used to compare a DES model to the conventional deterministic approaches. In a DES environment coupled with a system dynamics model, Alzraiee, Zayed, and Moselhi (2015) studied a hybrid project planning and scheduling method on a Critical Path Method (CPM) -based network. Regarding the uncertainties of the project costs and durations, the proposed hybrid modelling method sought to obtain realistic project networks and discover the interconnections of the project's components. Botín, Campbell, and Guzmán (2015) explored a very complex mine development system by integrating a stochastic DES with a Monte Carlo simulation and PERT to minimize the pre-production development period. For planning a hydroelectric project, Mubin, Jahan, and Gavrishyk (2019) investigated a time-cost trade-off problem using Monte Carlo simulation to analyze the project completion risk. Using discrete-event simulation, Moreno et al. (2020) proposed the fixed start technique for construction projects. By regulating the start time of the activities, the approach aimed to meet the project deadline while reducing the variability in project delay. By combining DES with a genetic algorithm, Nili, Taghaddos, and Zahraie (2021) introduced a new simulation-based optimization approach for obtaining the best sequence of tasks in maintenance projects such that the costs are minimized.

Even though there have been several studies on project management, multi-scenario simulation modelling of a project planning problem considering project crashing has not been thoroughly investigated in the literature. In this paper, a simulation-based approach is proposed to optimize time-cost trade-off project planning problem under uncertainty. By using random activity durations, the stochastic nature of the model representing the uncertainties in project execution is addressed. A multi-scenario framework is developed by creating various activity crashing scenarios in which the durations of the activities are shortened by allocating additional resources causing additional cost. A case study on a mine development project is conducted to validate the proposed model. Hence, this paper offers a thorough analysis of the impacts of uncertainty and multiple project crashing scenarios on project cost and completion time.

The novel contribution of this study is the introduction of a simulation-based optimization algorithm to address the project scheduling problem under uncertainty, considering project deadline and budget constraints. The algorithm also allows for the identification of critical project activities, statistical analysis of activity criticalities and project completion time, as well as the development of multiple project crashing scenarios to minimize total cost and completion time.

The proposed methodology and algorithm are presented in Section 2, followed by a numerical example and computational results in Section 3.

Finally, the study concludes with closing remarks and suggestions for future research in Section 4.

3 METHODOLOGY

3.1 Network Models

The network analysis in project planning, scheduling, and controlling has become a common application in the past decades. The CPM and the PERT, both proposed in the late 1950s, are the two most popular network-based project management techniques (Kelley and Walker 1959; Winston 2004). They are effective methods for identifying the critical tasks and the shortest completion time and assessing the impact of changes on project cost and duration (Agyei 2015; Lujić, Barković, and Jukić 2019). These methods also introduced the concept of "project crashing", which involves allocating more labour, equipment, and material to one or more project tasks to reduce total project duration. Project crashing must be applied based on a trade-off analysis between project duration and cost because increasing the number of resources leads to additional project cost. The trade-off between time and cost can be seen in Figure 1.

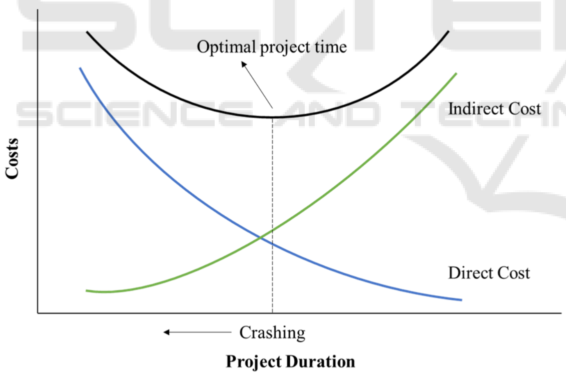

Figure 1: Time-Cost Trade-off.

The project network can then be constructed based on Activity-On-Arc (AOA) graph or Activity-On-Node (AON) graph. CPM is a deterministic method to schedule well-defined activities assuming that all activities can be scheduled with certainty. On the other hand, PERT is a probabilistic method where the uncertainties in each activity duration are considered and the probability of completing the project within a given deadline can be estimated. For the estimation of duration values of each activity i, three-point estimates, which are the optimistic estimation a_i , the most likely estimation m_i, and the pessimistic estimation b_i are utilized. Considering T_i is the duration of activity i, PERT requires the assumption that T_i follows a beta distribution. Thus, the mean and variance of T_i may be approximated by Eq. (1-2).

$$E(T_i) = \frac{a_i + 4m_i + b_i}{6} \quad (1)$$

$$var(T_i) = \frac{(b_i - a_i)^2}{36} \quad (2)$$

PERT requires the assumption that the durations of all activities are independent. Then for any path in the project network, the mean and variance of the time required to complete the activities on the path are given by Eq. (3-4).

$$\sum_{i \in path} E(T_i) \quad (3)$$

$$\sum_{i \in path} var(T_i) \quad (4)$$

One of the most difficult problems in project planning is finding a trade-off between time and cost that will allow the project to be completed within the specified deadline while minimizing costs. The project length can be shortened by crashing the critical activity durations to meet the deadline of the project. Crashing is achieved so that the critical activity durations are shortened by assigning additional resources to them. Thus, the objective is to shorten the project duration while minimizing the crashing cost. The relationship between normal time and cost, and crash time and cost are represented in Figure 2.

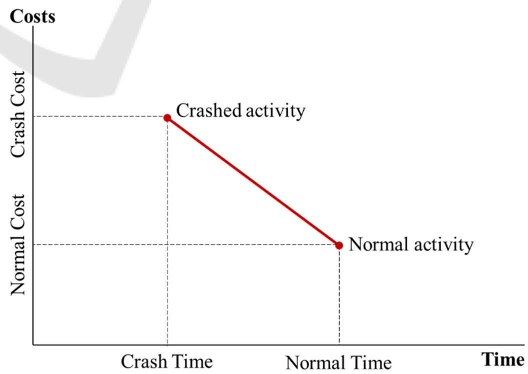

Figure 2: The Relationship between Normal Time and Cost, and Crash Time and Cost.

The normal point on the graph corresponds to the time and cost of the activity when it is executed in the normal way. On the other hand, the crash point represents the time and cost when the activity is fully crashed. The crash cost per period for each activity in the network can be calculated using Eq. (5), assuming that the crash costs are linear over periods.

$$\frac{Crash\ cost - Normal\ cost}{Normal\ time - Crash\ time} \tag{5}$$

3.2 Discrete-Event Simulation Model

Discrete Event Simulation (DES) is a dynamic simulation technique that can be used to model a project management system that has a discrete sequence of activities over the project duration. It is a powerful technique in terms of the modelling of uncertain and complex project management problems. In this study, a dynamic, stochastic, and discrete-event simulation model is developed based on PERT.

In this study, a stochastic simulation-based approach is proposed to examine the trade-off between time and cost of a project planning problem under the project deadline and budget constraints. Randomized activity durations are used to address the stochastic structure of the model, and a multi-scenario framework is developed by creating various activity crashing scenarios. Thus, determining the impact of uncertainty and project crashing scenarios on project completion time and cost is detailed in the current study. The DES model is used to identify bottlenecks in the project network and estimate the risks related to the project's uncertain characteristics. The objective of simulation-based optimization is to find the best solution among multiple project crashing scenarios such that the total cost of the project and its completion time is minimized.

The project is divided into tasks in accordance with the work breakdown structure (WBS). The project network is established as an Activity-On-Node (AON) graph $G(N, A)$, where N denotes the node sets identifying project activities and A denotes the arc sets indicating the precedence relationships between those activities. There are n different project activities in the established network model. The predecessor and successor activity sets are designated as J_i and K_i, respectively, for each activity i. Using the crashed activity times X_i and stochastic activity durations D_i for each activity i, the precedence relationships between activities are developed by calculating the earliest start ES_i and earliest finish EF_i times in the forward pass, and the latest start LS_i and latest finish LF_i times in the backward pass, through the network. The project completion time and the critical path are determined based on the parameters calculated in forward and backward passes. The normal cost NC, delay cost DC, and crashing cost CC are obtained at the end of the simulation run. The normal cost is calculated as the summation of each activity execution cost, NCP_i. By multiplying the delayed number of periods by the delay penalty P, the delay cost, which only occurs if the project completion time T_{pc} exceeds the target project time T_t , is determined. In addition, the crashing cost is obtained by multiplying the duration of the crashed activity X_i by the activity's associated crash cost per period, CCP_i. As a result, the function consisting of these three cost items is given as the project's total cost function TC in the proposed simulation model. The model also incorporates an optimization tool where the objective function and constraints of the network are introduced. The equations specified in the optimization tool to minimize the function of the total project cost are displayed below.

$$Minimize\ f_1(x) + f_2(x) + f_3(x) \tag{6}$$

$$f_1(x) = \sum_i (NCP_i) \tag{7}$$

$$f_2(x) = \left(T_{pc} - T_t\right) \cdot P \tag{8}$$

$$f_3(x) = \sum_i (X_i \cdot CCP_i) \tag{9}$$

$$TC \leq B_{max} \tag{10}$$

$$T_{pc} \leq T_{max} \tag{11}$$

The overall project cost, including normal, delay, and crashing cost, is minimised by Equation (6), respectively. Equations (10) and (11) make sure that the project budget B_{max} and project deadline T_{max} cannot be exceeded by the total project cost TC and project completion time T_{pc}, respectively. In addition, the system's control and response variables are chosen for the simulation-based optimization approach. The decision variables of the system are referred to as control variables, whereas the output of a simulation run includes the response variables.

The crashing times of the activities, which are measured as the difference between the normal execution time and the shortest completion time of the activity, are defined as the decision variables of the system. As a result, multiple scenarios are built using numerous crashing time combinations for the activities. Hence, a stochastic discrete-event simulation model is developed to obtain the optimal project schedule, yielding the cost-wise best scenario among all.

4 CASE STUDY

Mining construction projects are made up of operational activities that take place over a predetermined time. To reveal the model's capability and applicability, the proposed simulation model is applied to an electrical substation construction project conducted in a mine. Table 1 represents the construction project consisting of 19 activities. Precedence relationships and activity durations are determined based on expert opinions. Activity durations are represented as minimum, most likely, and maximum duration required to complete the corresponding activity. The activity list includes every step of electrical substation building, from conducting economic feasibility study to supplying power.

Table 1: Activity list of the electrical substation construction project.

ID	Predecessors	Duration (days)
1	-	(38,56,60)
2	1	(25,28,35)
3	2	(15,19,25)
4	3	(75,84,152)
5	3	(90,105,125)
6	3	(12,14,17)
7	6	(8,11,14)
8	6	(12,15,20)
9	6	(5,6,8)
10	7,8,9	(30,34,40)
11	10	(38,40,45)
12	5,11	(48,52,54)
13	5,11	(14,18,22)
14	12,13	(44,48,53)
15	12,13	(17,20,23)
16	4,14	(57,62,65)
17	15,16	(10,12,15)
18	17	(15,18,22)
19	18	(0,0,0)

On this basis, Arena® Simulation Software is used to build the activity network diagram in a dynamic simulation environment. The simulation model is run considering the deterministic input dataset which is addressed as the most likely activity duration given in Table 1. As shown in Figure 3, the critical path includes 10 activities, including 1, 2, 3, 5, 12, 14, 16, 17, 18, and 19. The calculated time to complete the project is 400 days.

Following the introduction of the stochastic input dataset as probability distributions, the developed algorithm is computed to identify the project bottleneck activities and analyse the risk associated with project completion time under stochastic activity durations. Activity durations are designated by assigning random numbers from triangular distributions with the parameters of minimum, most likely, and maximum activity durations, as they are given in Table 1.

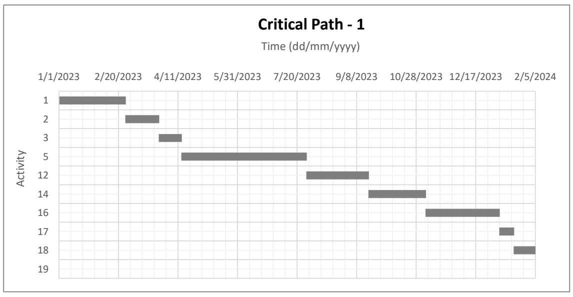

Figure 3: The Critical Path Schedule for Path-1.

The simulation model is replicated 1,000 times to remove the initial bias when a balancing point is found, because of the stochasticity included into the model. This approach enables estimation of the distribution of the project completion times and the associated uncertainty in the level of desired relative precision. According to the given random activity durations, the constructed model selects one of three paths as the critical path, as shown in Figure 3, 4 and 5. Activities 1, 2, 3, 12, 14, 16, 17, 18, and 19 are present on both paths. Since their probability to be on the critical path is determined as 100%, they are designated as bottleneck activities. The probability of occurrence of Path-1 is calculated as 54.9%, Path-2 as 44.6%, and Path-3 as 0.5%.

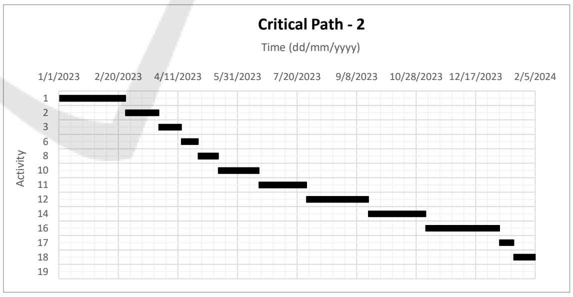

Figure 4: The Critical Path Schedule for Path-2.

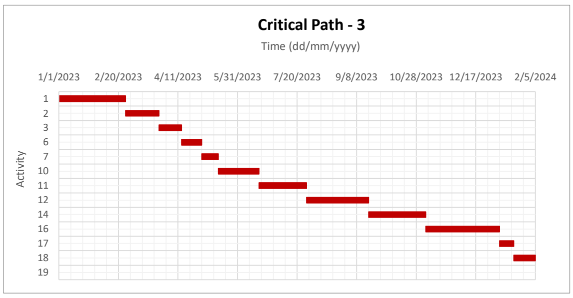

Figure 5: The Critical Path Schedule for Path-3.

In addition, the project completion times are fitted into the best distributions. A normal distribution with a mean of 401.2 days and a standard deviation of 8.1 days is discovered to be able to accurately predict project completion durations. The histogram of the original output data and the fitted normal distribution are shown in Figure 6. Based on the stochastic activity durations, it is evident that the project will be completed within 414.46 days with a 95% probability. Additionally, it is observed that there is a 44.22% probability that the project will be completed within 400 days. In contrast to deterministic approach, stochastic model produces probabilistic data that takes project uncertainties into account, allowing the risk of delay to be evaluated. The outcomes under these uncertainties demonstrate how the deterministic approach deviates significantly in terms of project completion time.

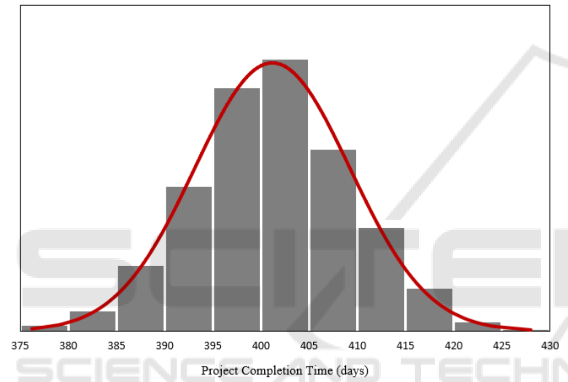

Figure 6: Fitting Normal Distribution for Project Completion Times without Crashing.

Besides, the simulation-based optimization model is modified to consider multiple project crashing scenarios to reduce the overall project cost while still adhering to the deadline and budget constraints. The objective function and the constraints specified by Equation (6-11) are included into the simulation model using the OptQuest® for Arena® Simulation Software. The crashed activity durations are defined as the control variables of the system. Based on the maximum crashing times listed in Table 2 and the step of 5, 6,912 different crashing scenarios are generated and integrated into the model. As the response variables of the system, the activity criticality, crashed durations, all the cost items, and the project completion time factors are indicated. Thus, the stochastic simulation algorithm is solved such that the optimal project completion time is attained through project crashing, giving the best output among all the scenarios in terms of costs.

Table 2: Maximum crashing time of the activities.

ID	Maximum Crashed Time (days)
5	25
6	5
10	10
11	15
12	15
14	10
16	15

The simulation results of the project crashing scenarios are shown in Figure 7. Crashing is seen to reduce project completion time while gradually increasing project cost. Similarly, as the delay penalty is only paid when the project completion time reaches a threshold value, which is set at 330 days, the delay cost steadily rises as the project completion time increases. Moreover, based on these two cost elements, the project cost indicates a trade-off point, showing the financially best schedule. The project completion time of 342 days results in the best solution.

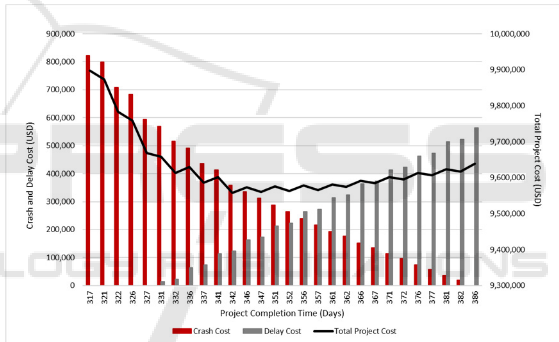

Figure 7: Multi-Scenario Simulation Results on Cost Items.

According to the results, the critical path is seen to span 10 activities, including 1, 2, 3, 5, 12, 14, 16, 17, 18, and 19, as shown in Figure 3. The optimal crashed durations are demonstrated in Table 3 for the cost-wise best scenario. The overall project cost is calculated at $9,557,588.98 with 70 days of crashing, with 94.95% of it being seen as normal cost, 3.76% as crashing cost, and 1.29% as delay cost.

Table 3: Optimal crashed durations of DES solution.

ID	Optimal Crashed Time (days)
5	25
6	5
10	10
11	15
16	15

Considering of the cost-wise optimal scenario with the crashing durations listed in Table 3, the simulation model is replicated 1,000 times and the statistical analysis showed that the model constructs three paths as the critical path, each of which covers the activities 1, 2, 3, 12, 14, 16, 17, 18, and 19. Since there is a 100% probability that these activities will occur on the critical path, they are identified as bottleneck activities. The schedules of Path-1, Path-2, and Path-3 is depicted in Figures 3, 4, and 5, respectively. The probability of occurrence of Path-1 is calculated as 77.4%, Path-2 as 22.3%, and Path-3 as 0.3%. In addition, the project completion times are fitted into the best distributions. A normal distribution with a mean of 359.5 and a standard deviation of 8.8 is also indicated to be able to identify the project completion times. The histogram of the original output data is shown in Figure 8, and the fit line indicates the line of the normal distribution.

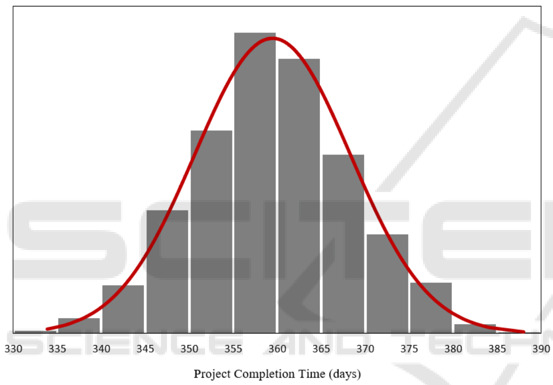

Figure 8: Fitting Normal Distribution for Project Completion Times with Crashing.

The probability that the project will be completed within 342 days is computed as 2.34%, when the stochastic activity durations and 70 days of crashing activity are considered. Additionally, it is observed that the project will be completed within 374 days with a 95% probability.

5 CONCLUSIONS

Predicting overall project cost and project completion time is especially difficult for time-sensitive engineering projects when operational uncertainties are extremely noticeable. The timing of a construction project is crucial in the mining industry since a mining operation's worth depends on the gaps in the commodity price of the mineral produced, price cycles, the degree of market demand, the size of the costumers, and sales potential. The risk of a project should be controlled in accordance with the company's willingness to take operational and financial risk, which is highly variable depending on the nature and objectives of the project.

In this study, a discrete-event simulation model with multiple crashing scenarios is developed for the time-cost trade-off project planning problems considering stochastic and dynamic structure. The model is then applied for an electrical substation construction project conducted in a mine with the total of 19 activities. To describe the scheduling of activities, the basic project network is built as an Activity-On-Node graph. The Arena® Simulation Software is used to construct and run the model with deterministic input dataset, and the project completion time is observed as 400 days. On the other hand, the criticality of the activities is assessed, and the bottlenecks of the project are identified based on simulation replications carried out with stochastic input dataset. Statistical analysis is conducted on the outputs of project completion times from 1,000 simulation replications. When stochastic activity durations are considered, it is shown that there is a 44.22% probability that the project will be completed within 400 days. Additionally, the multiple crashing scenarios are integrated into the simulation-based optimization model to minimize the overall project cost under deadline and budget constraints. The objective function and the constraints are established and included in the generated simulation model using the OptQuest® for Arena® Simulation Software. In the cost-wise best scenario, the total project cost and the project completion time are calculated as $9,557,588.98 and 342 days, respectively, with a total of 70 days of project crashing. 1,000 simulation replications are run to find the best solution for the DES model giving the most cost-effective scenario considering the crashing durations, and the results are statistically analysed. It is observed that the project duration can be reduced by 9.89% under stochastic activity durations, and the crashing durations obtained from the best-case scenario of the DES model. The project's outcomes produced a collection of representations that reflect an equally probabilistic understanding of reality including the uncertainties encountered throughout project execution. Using this, the decision-makers can make inference about the risk of projects.

The model can be expanded in future research to projects with more complicated structures. Further research can focus on resource availability constraints. On this basis, robust schedules can be created that consider various schedule interruptions, such as resource shortages and disruptions in the material supply chain. Furthermore, the activity disruptions, caused by environmental and operational conditions such as the seasonality effect, can be integrated to have more accurate schedules.

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