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Optimizing Project Schedules under Uncertainty: A Hybrid Approach to Crashing and Risk Evaluation Using Monte Carlo Simulation and Integer Linear Programming

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Abstract: The optimization of project schedules in the presence of uncertainty remains a critical challenge in project management. This study proposes a hybrid methodology that combines Monte Carlo Simulation (MCS) with Integer Linear Programming (ILP) to optimize project crashing strategies under conditions of schedule risk. The approach was applied to a real-world telecommunications infrastructure project, which involved the construction of 50 towers within a stringent contractual deadline. MCS was employed to model the uncertainty in activity durations and assess the likelihood of on-time project completion, while ILP was used to determine the most cost-effective crashing strategy. The findings indicate that, without any mitigation measures, the probability of completing the project within the planned 68-day schedule was a mere 3%. However, upon implementing risk response measures, this probability increased to 21%. A comparative analysis demonstrated that delay penalties increase at a much higher rate than crashing costs, highlighting the significant financial benefits of early intervention. This study illustrates that the integration of probabilistic risk analysis with optimization techniques not only enhances schedule reliability but also minimizes cost overruns, providing a robust decision-making framework for complex projects. By leveraging the combination of MCS and ILP, the proposed methodology supports the development of more resilient and economically efficient project plans, particularly in projects characterized by high uncertainty and time-sensitive constraints.

Keywords: Project crashing; Optimization; Risk analysis; Integer Linear Programming (ILP); Monte Carlo Simulation (MCS); Time-cost trade-off

1 Introduction

In today's highly competitive industrial landscape, large-scale engineering and infrastructure projects are increasingly constrained by tight schedules, limited budgets, and heightened stakeholder expectations. The demand for rapid deployment of capital-intensive ventures has elevated the significance of effective project planning and control [1]. However, despite advances in project management methodologies, a substantial number of projects still experience schedule overruns and budget excesses [2]. This is particularly true in sectors such as construction, oil and gas, power generation, and manufacturing, where external disruptions and internal inefficiencies frequently derail planned timelines [3, 4]. The complexity of interdependent activities, the variability in resource availability, and the unpredictable nature of external risk factors contribute to considerable uncertainty in project execution [5]. As a result, the traditional deterministic approaches to project scheduling often fall short of delivering realistic and robust plans, thereby necessitating more sophisticated, risk-aware models for schedule optimization.

The time-cost trade-off problem has long been recognized as a central issue in project management, particularly when stakeholders seek to accelerate completion without disproportionately increasing costs [6]. The fundamental principle involves expediting critical activities through additional resources, commonly referred to as "crashing", to shorten the project duration [7]. However, crashing comes with incremental direct costs and often introduces new layers of risk. Balancing the cost of crashing with potential delay penalties or opportunity costs requires a nuanced understanding of project dynamics and cost functions [8]. Prior studies have demonstrated that this optimization challenge is inherently combinatorial, demanding advanced mathematical tools for tractable solutions. The interrelation between crashing strategies and overall project risk has been insufficiently addressed in earlier research, where schedule compression and risk management are often treated as disjointed domains. Bridging this gap is critical for developing comprehensive planning tools that enable project managers to make risk-informed decisions under time and cost constraints [9].

Conventional scheduling methodologies such as the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT) have formed the backbone of project planning tools for decades [10]. While these methods offer logical sequencing and network-based visualizations of project activities, they inherently assume deterministic durations and ignore the probabilistic nature of real-world project execution [11]. In particular, CPM fails to account for uncertainties in activity durations, rendering it less effective in complex projects characterized by volatile risk factors. PERT attempts to introduce variability through three-point estimates, yet it is limited by its inability to accurately assess path convergence and merge point risks. Studies have shown that PERT often underestimates schedule risks and does not accommodate the possibility of multiple near-critical paths, which are prevalent in real project networks. Consequently, reliance on traditional CPM/PERT frameworks may result in misleading expectations, inadequate risk mitigation strategies, and suboptimal schedule forecasts [12, 13].

To overcome the limitations of deterministic scheduling, the integration of stochastic methods such as MCS has become increasingly prominent in both academic research and industrial applications [14]. MCS allows project planners to simulate thousands of potential project scenarios by treating activity durations as probability distributions rather than fixed values [15]. This approach enables a more realistic assessment of schedule variability and the likelihood of meeting specific milestones [16]. Monte Carlo-based schedule risk analysis not only identifies the most vulnerable activities but also quantifies the probability of project completion within a given timeframe. Furthermore, tools such as Primavera Risk Analysis and @Risk have incorporated MCS into their scheduling engines, making the technique accessible to practitioners. The strength of MCS lies in its ability to capture the aggregate effects of uncertainties across complex network paths, allowing for data-driven decisions about risk mitigation and resource allocation.

While MCS effectively addresses the uncertainty dimension of scheduling, it does not inherently prescribe optimal crashing strategies. For this, researchers have turned to mathematical programming techniques, including linear programming (LP), ILP, dynamic programming, and hybrid heuristics [17–19]. These methods enable the formulation of time-cost optimization models that respect logical precedence constraints while minimizing total project cost, including both crashing expenses and delay penalties. Recent developments have integrated piecewise linear cost functions to more accurately reflect real-world resource pricing. Software tools such as ILOG and CPLEX are widely used to solve such optimization problems, offering robust solvers for large-scale project models. Notably, ILP models allow discrete representation of time segments and binary decisions regarding whether to crash specific activities. When integrated with MCS outputs, these optimization models provide powerful hybrid frameworks for risk-adjusted project planning.

Despite substantial progress in both simulation and optimization techniques, relatively few studies have succeeded in integrating these two paradigms into a unified decision-support framework. Most literature treats risk analysis and schedule optimization as sequential rather than interdependent tasks. However, real-world project management requires simultaneous consideration of uncertainty, resource limitations, crash cost escalation, and contractual penalties. Hybrid approaches that combine MCS for risk assessment and IP for optimization hold significant promise in this regard. These models offer a holistic evaluation of project feasibility under uncertainty and support proactive decision-making during the planning and bidding stages [20, 21]. Moreover, such integrated models can inform contract negotiations by quantifying schedule buffers, risk premiums, and contingency requirements. This study aims to extend the literature by developing and demonstrating a hybrid project crashing model that accounts for both stochastic schedule variability and cost-driven optimization in a risk-informed environment.

2 Methodology

The methodology adopted in this study integrates probabilistic schedule risk assessment with a mathematical optimization model to develop an effective time-cost trade-off strategy under uncertainty. The hybrid framework is designed to support project managers in identifying critical schedule risks, evaluating potential delays, and formulating cost-efficient crashing strategies [22]. This approach comprises two major components: (1) MCS for project schedule risk analysis and (2) ILP for optimizing the project crash plan. The two components are sequentially applied yet interrelated, as the simulation results guide the selection of activities to be considered for crashing in the optimization stage. The methodology captures both the stochastic nature of activity durations and the cost implications of schedule compression, thereby offering a comprehensive decision-support mechanism that enhances the reliability of project planning under uncertainty.

The first stage of the methodology involves conducting a detailed schedule risk analysis using MCS. A baseline project schedule is initially developed using Primavera P6, including all defined activities, precedence relationships, and estimated durations. For each activity, a three-point estimate, comprising optimistic, most likely, and pessimistic durations, is established through expert judgment in risk workshops. These estimates are used to construct triangular probability distributions representing the uncertainty of activity durations [23]. The project schedule is then imported into Primavera Risk Analysis software, where MCS is executed with a large number of iterations. The output includes probability distributions of total project duration, critical path analysis, and schedule sensitivity indices. These results highlight the most risk-sensitive activities and the probability of meeting contractual deadlines, serving as the analytical basis for targeted schedule interventions [24].

Following the simulation, a schedule sensitivity analysis is performed to identify the most critical and risk-prone activities. This is achieved by evaluating the correlation between individual activity durations and the overall project completion date [23]. Activities with the highest schedule sensitivity index are prioritized for further analysis, particularly those that lie on the critical path or near-critical paths. The critical path is revalidated under uncertainty to ensure that risk-induced variability does not shift the sequence of schedule-dominant activities. This step ensures that only the most impactful activities are included in the optimization model, thereby enhancing the efficiency and computational tractability of the ILP formulation. The output of this phase includes a refined list of critical activities and a corresponding network diagram, which forms the structural foundation for the subsequent optimization model.

The second stage of the methodology applies ILP to determine the optimal crashing strategy for the selected critical path. A network-based model is formulated to minimize the total project cost, which includes direct crashing costs and delay penalties. The decision variables represent the start times of nodes, crash durations for each activity, and binary indicators for selecting crash segments. Constraints are imposed to enforce precedence relationships, limit crash durations within allowable ranges, and ensure logical feasibility [25]. The objective function is designed to minimize the sum of crashing costs and penalties for late completion, if applicable. The outputs include optimal crash durations for each selected activity, total project cost, and project duration under different risk scenarios (e.g., average, most likely, pessimistic). This process enables the identification of cost-effective strategies for schedule acceleration while balancing the trade-offs between crashing expenses and contractual penalties [26, 27].

The final step involves synthesizing the insights gained from MCS and ILP optimization to support robust project decision-making. By integrating probabilistic schedule analysis with cost-optimized crashing strategies, the methodology provides a multi-dimensional evaluation of project feasibility. This includes estimating the likelihood of on-time completion, quantifying the cost implications of various crash plans, and determining whether schedule acceleration is justified under prevailing risk conditions. The comparative analysis of scenarios, such as average time, most likely time, and pessimistic time, further aids in sensitivity testing and contingency planning. The results inform project stakeholders during the planning and bidding phases, enabling data-driven negotiation of contract schedules, buffer times, and risk-sharing mechanisms. Ultimately, the proposed methodology offers a structured and replicable approach to managing time and cost risks in large-scale engineering and construction projects.

3 Results

Libya's geographic location at the crossroads of North Africa and the Mediterranean basin grants it significant strategic importance, both regionally and internationally [28, 29]. As the country moves toward stabilization and economic revitalization, there has been renewed focus on infrastructure development as a catalyst for national growth and regional integration [30]. In recent years, a number of large-scale engineering and telecommunications projects have been initiated to enhance connectivity, support digital transformation, and stimulate economic activity across key urban centers [31]. These efforts reflect a broader national agenda aimed at modernizing essential services and improving access in underserved areas.

The case study involves the application of MCS and ILP modeling for project scheduling under risk conditions. It pertains to the construction of 50 telecommunications towers, each 40 meters high, in the city of Misrata, Libya, for a mobile phone service provider in the central region. The project was awarded under a contract valued at 12,600,730 Libyan dinars and was to be completed within a period of 68 days. To meet this deadline, 50 teams were mobilized to work simultaneously. The daily working schedule was set at 10 hours per day with no weekly breaks. The contractor subcontracted portions of the work to local companies. Each telecommunications tower occupies a total area of 144 square meters (12m × 12m). A delay penalty of 0.1% of the total contract value per day was imposed, with the total penalty not to exceed 10% of the contract value.

Information is collected from project experts as well as from previous similar projects to estimate the optimistic, most likely, and pessimistic duration values for each risk item encountered during the project. The Primavera Risk Analysis software is then used to simulate the probable project duration under risk conditions. A simulation with 3,000 iterations is performed to estimate the project completion time, using Latin Hypercube Sampling as the simulation method. In each iteration, the durations of project activities and the impact of risks on those activities are assessed. In addition, the simulation software enables the estimation of overall project costs under risk scenarios. Based on the information obtained from the contract documents, the project was scheduled using the software by developing the work breakdown structure (WBS), defining the activities, and specifying the duration, start date, and end date for each activity. With the support of domain experts and through the risk registers of previous projects, the key risks affecting the project schedule and their likelihood of occurrence were identified. All potential risks were then entered into the simulation software, as illustrated in Figure 1.

Risk		
ID	T/O	Title
001	T	the soil of the tower site is not suitable
002	T	the hardness of the concrete isn't appropriat
003	T	the tower is not straight
004	T	the grounding value isn't appropriat
005	T	The security situation of the country isn't stable
006	T	natural factors
007	T	Problems between the contractor and the supervising engineer
008	T	the Entries and work permitios of security institutions and ag...
009	T	The owner's desire to terminate the contract

Figure 1. Input of potential project risks into the simulation software for schedule risk analysis

The baseline project schedule was reviewed prior to incorporating risk probabilities into the activities. Multiple iterations were performed using optimistic, most likely, and pessimistic duration estimates for each activity. As illustrated in Figure 2, the simulation results showed that the project has a 24% probability of being completed within 68 days. The maximum estimated duration reached 82 days, while the probability of completion within 74 days was approximately 80%.

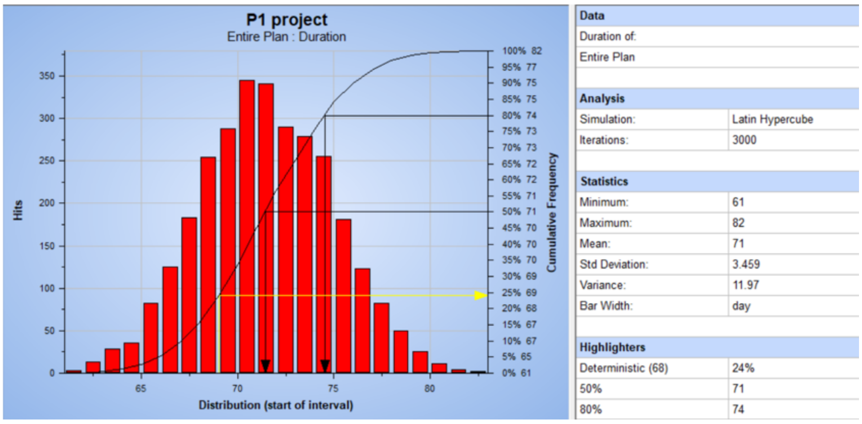

Figure 2. Project duration distribution before risk mitigation

Figure 3 presents the estimated total project cost based on the probabilistic activity duration estimates. The results indicate that, at the 80% confidence level, the total cost is estimated at 12,686,037 LYD, while at the 100% confidence level, the cost reaches 12,777,245 LYD.

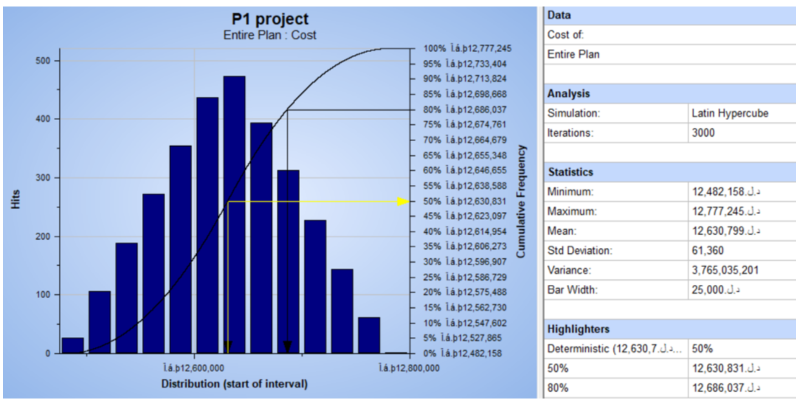

Figure 3. Estimated project cost before risk mitigation

As shown in Figure 4, the relationship between project duration and total cost is illustrated. The green-shaded area represents a region where both time and cost are relatively low, accounting for approximately 12% of the total cost and 24% of the maximum project duration, which depicts the latest possible project completion date. The first black-shaded segment (12%) reflects a scenario characterized by high costs and short activity durations, not exceeding 14% of the project timeframe. The second black-shaded segment (38%) corresponds to long activity durations with relatively low costs. Meanwhile, the red-shaded area (38%) indicates an undesirable scenario where both cost and duration are high, suggesting a phase of inefficiency and reduced cost-effectiveness.

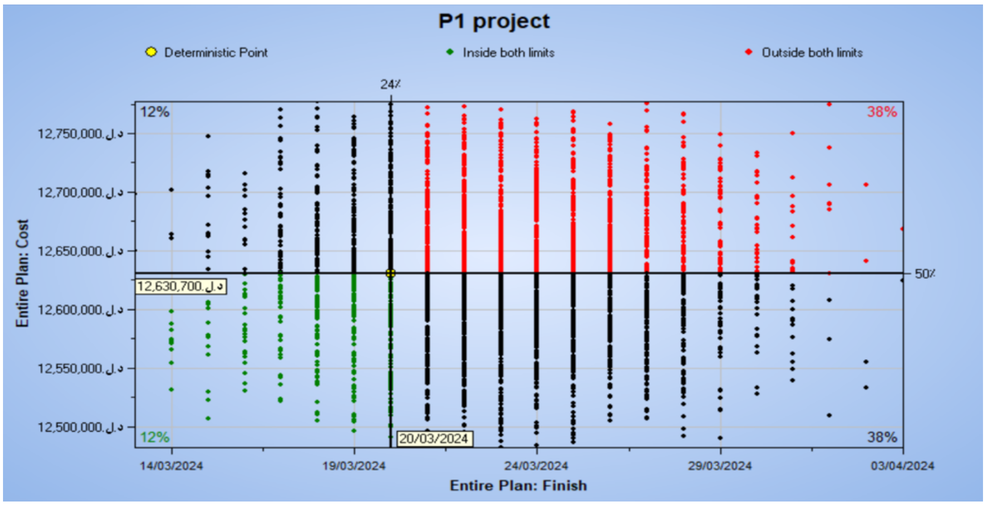

Figure 4. Relationship between project duration and total cost

After incorporating the identified risks into the project activities and running the MCS with 3,000 iterations, the impact of these risks on the project schedule prior to implementing any mitigation measures is illustrated in Figure 5. The results show that there is an 80% probability of completing the project within 88 days, and a 100% probability of completion within 118 days. In comparison to the originally planned schedule of 68 days, the probability of meeting this target duration is only around 3%. Therefore, risk mitigation actions are necessary to reduce the impact of these risks on the overall project timeline.

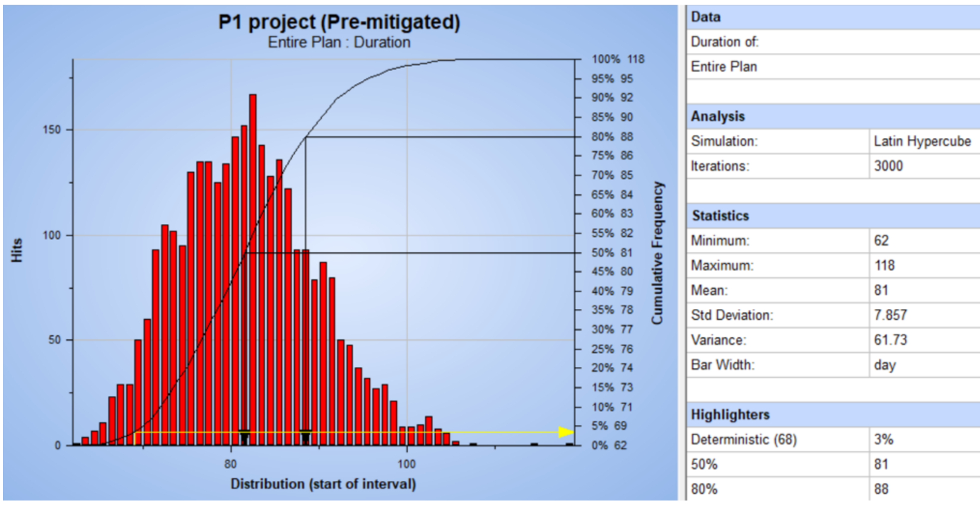

Figure 5. Project duration distribution after risk inclusion and before mitigation

Figure 6 illustrates the cost increase resulting from delays in the project schedule due to the impact of identified risks. A clear cost escalation is observed when compared to the earlier baseline schedule based on activity duration estimates. At the 80% confidence level, the estimated project cost rises to 12,798,657 LYD, while at the 100% confidence level, the total cost reaches 13,016,252 LYD.

Using Primavera Risk Analysis, the risk response strategy was defined, with risk mitigation selected as the preferred approach for addressing activity-level risks. Figure 7 presents the project schedule after implementing the mitigation measures and running the simulation with 3,000 iterations. The results indicate that, following risk mitigation, the probability of completing the project within 74 days is 80%, and within 86 days is 100%. Compared to the original planned duration of 68 days, the probability of meeting the initial target increases to approximately 21%.

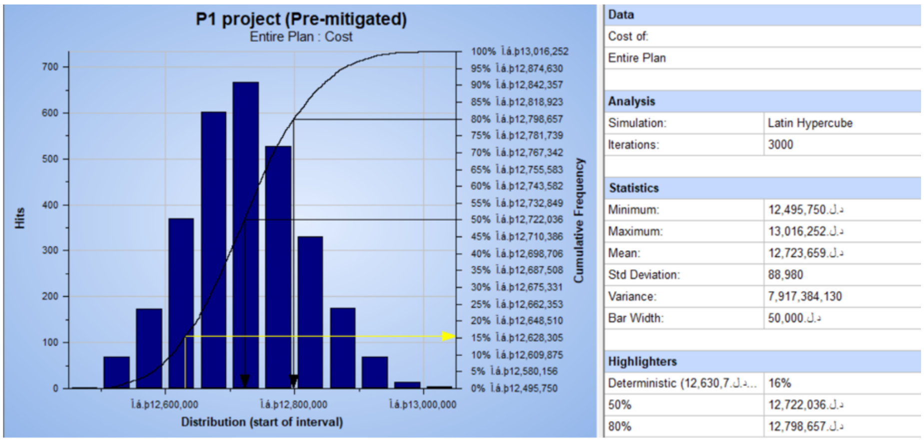

Figure 6. Estimated project cost after risk inclusion and before mitigation

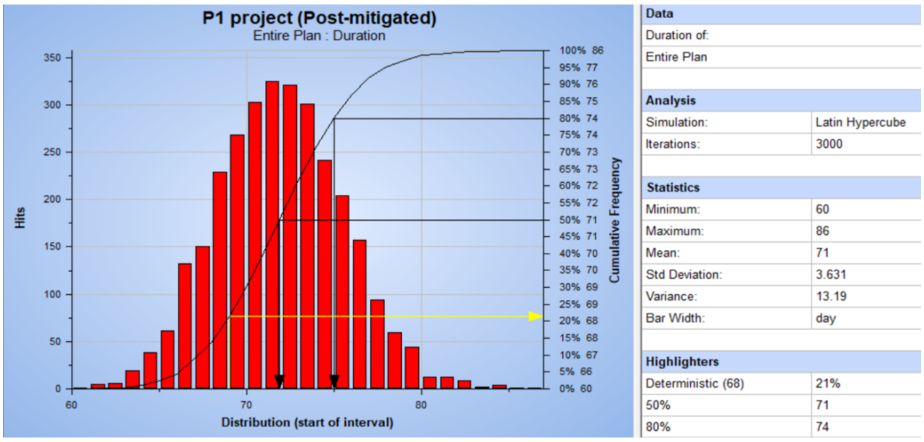

Figure 7. Project duration distribution after applying risk mitigation measures

As shown in Figure 8, the project cost changes after implementing the risk mitigation measures. Compared to the cost estimated under the initial activity duration assumptions, an increase in total cost is observed. At the 80% confidence level, the cost is estimated at 12,999,076 LYD, while at the 100% confidence level, the cost reaches 13,097,588 LYD.

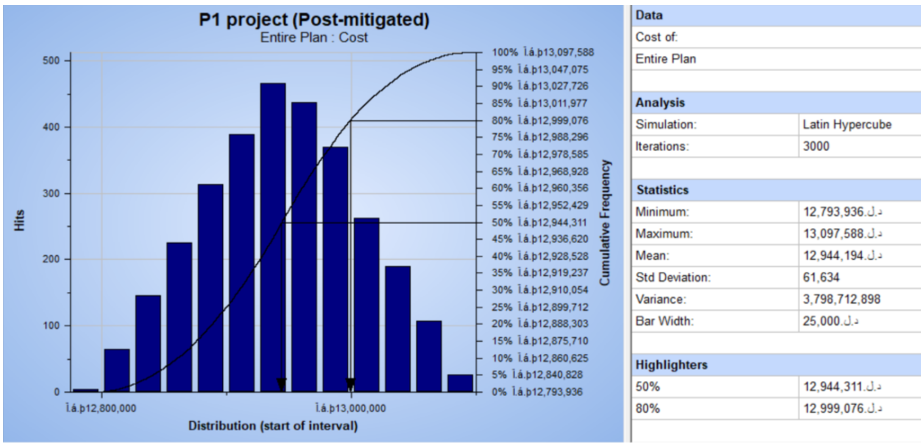

Figure 8. Estimated project cost after risk mitigation

Table 1 summarizes the results of the MCS, providing a comparative overview of the project schedule under different scenarios. The terms P80 and P100 represent 80% and 100% probability levels, respectively. The probability of completing the project within the initially planned duration of 68 days is only 3% under risk conditions, with the projected completion extending to 118 days. However, after implementing risk response measures, the probability of meeting the planned schedule increases to 21%, with the project expected to be completed in 86 days.

Table 1. Summary of project duration under different risk scenarios

Description	Deterministic Probability	Standard Deviation	P 80% (days)	P 100% (days)
Pre-analysis	24%	3.459	74	82
Pre-mitigation	3%	7.857	88	118
Post-mitigation	21%	3.631	74	86

The work activities, along with a logical network diagram and the duration of each activity on the critical path, were obtained through the project schedule network analysis. Figure 9 presents the critical path diagram generated.

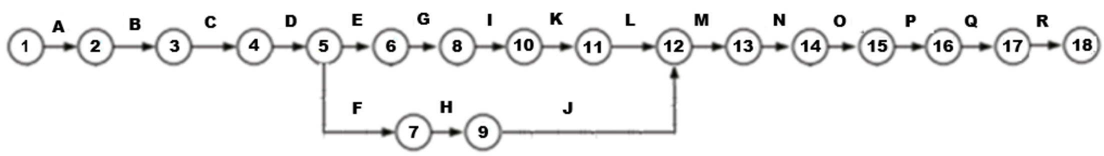

Figure 9. Critical path diagram

In the average time scenario, the project crashing cost is 53,285 LYD, while the delay penalty amounts to 202,080 LYD. In the most likely time scenario, the crashing cost is 88,579 LYD, with a delay penalty of 252,600 LYD. Under the pessimistic time scenario, the crashing cost rises to 291,884 LYD, and the delay penalty reaches 618,870 LYD. By comparing crashing costs with delay penalties, it is evident that both values increase as project delays become more severe. However, the rate of increase in crashing costs is less steep than the rate of increase in the total additional cost (i.e., the sum of crashing costs and delay penalties). This relationship is detailed in Table 2 and visually illustrated in Figure 10, which presents the costs of project delay, delay penalties, and the overall additional cost. Based on the extensive analyses conducted in this study, the company can determine the optimal execution strategy for each activity, allowing the project to be completed by the contractual deadline at the minimum possible cost.

Table 2. Comparison of crashing costs and delay penalties across different time scenarios

Duration	Project Crash time	Project Crash Cost	Penalty Cost (D.L)	Total Cost
Average time (days)	16	53285	202080	255365
Most likely time (days)	20	88579	252600	341179
Pessimistic Time (days)	49	291884	618870	910754

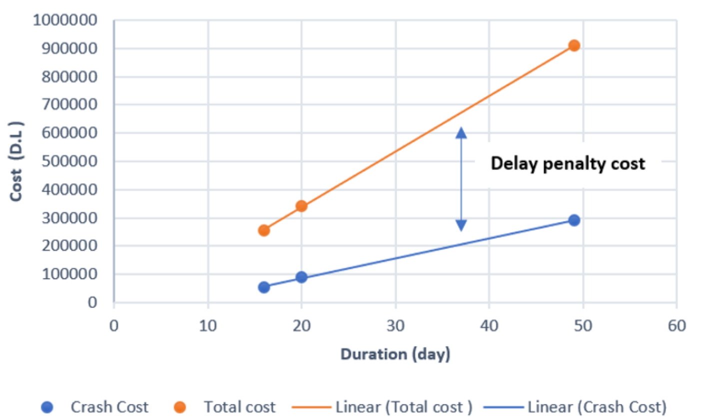

Figure 10. Cost of project delay, delay penalties, and total additional cost

4 Discussion

The simulation results clearly highlight the extent to which risk factors can significantly alter project timelines and associated costs. Without implementing mitigation measures, the probability of completing the project within the originally planned duration of 68 days was as low as 3%, with a projected maximum duration of up to 118 days. These findings underscore the inherent uncertainty in large-scale infrastructure projects, particularly those that involve simultaneous task execution and strict timelines. Moreover, the comparison between pre- and post-mitigation scenarios illustrates the value of proactive risk management, where the probability of on-time completion increased to 21% and overall project duration was notably reduced. These insights provide strong evidence for integrating risk response strategies early in the planning phase to enhance schedule reliability and minimize potential penalties.

The comparison of crashing costs and delay penalties across different time scenarios reveals important cost dynamics for decision-makers. Although both crashing costs and penalties increase as project duration extends, the marginal cost of delay rises more steeply than that of crashing. For example, in the pessimistic case, crashing costs reached 291,884 LYD, whereas delay penalties escalated to 618,870 LYD. This indicates that, from a cost-minimization perspective, adopting a crashing strategy, even when involving additional resource mobilization, can be more economical than accepting prolonged delays. This is particularly true when the contract includes strict penalty clauses. The analysis further suggests that timely intervention through selective activity crashing can effectively mitigate overall cost exposure, especially when applied to risk-sensitive tasks identified through simulation.

These findings offer practical insights for project managers operating in high-risk environments. The integration of MCS and ILP provides a robust hybrid framework for evaluating both schedule feasibility and cost optimization. Beyond technical accuracy, the results empower managers to make informed trade-offs between resource allocation and contractual compliance. Importantly, the model enables the identification of cost-effective execution strategies tailored to different risk scenarios, allowing for more flexible and responsive project control. This approach also supports risk-adjusted bidding, improved stakeholder communication, and the negotiation of realistic timelines. Overall, the study demonstrates that integrating quantitative risk analysis with optimization methods is not only analytically sound but also essential for achieving efficiency and reliability in complex project environments.

5 Conclusions

This study presented a hybrid framework that integrates MCS with ILP to address schedule and cost uncertainties in project planning. By applying this methodology to a real-world telecommunications infrastructure project, the research demonstrated the significant impact of risk on both project duration and total cost. The probabilistic analysis revealed that the likelihood of completing the project within the original contractual timeframe was critically low without mitigation, highlighting the importance of proactive risk response. Through simulation-based forecasting and optimization-driven crashing strategies, the project's feasibility was notably improved, both in terms of schedule adherence and cost efficiency.

The comparative evaluation of crashing costs and delay penalties across different scenarios further emphasized the economic advantage of strategic activity compression over passive delay absorption. The proposed approach offers project managers a practical decision-support tool for navigating uncertainty, optimizing resource deployment, and aligning execution plans with contractual obligations. Overall, the findings affirm that integrating stochastic risk modeling with optimization techniques enhances the reliability and cost-effectiveness of project delivery, particularly in high-risk, time-constrained environments.

Author Contributions

Conceptualization, I.B. and A.E.; methodology, A.E.; software, A.E.; validation, I.B.; formal analysis, A.E.; resources, A.E.; writing—original draft preparation, A.E., I.B; writing—review and editing, I.B.; project administration, I.B. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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