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# A Monte Carlo simulation to identify the effect of delays in construction project scheduling

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**Abstract** Construction projects are inherently complex and subject to various uncertainties and delays that can significantly impact their schedule and overall success. Delays in construction projects can arise from a multitude of factors such as weather conditions, material shortages, labor issues, or unexpected design changes. These delays not only disrupt the planned timeline but can also lead to cost overruns and conflicts among project stakeholders. An efficient construction industry is a prerequisite for the development of the construction process. In this regard, this paper aims to identify the most common, severe, and important causes of schedule delay and its effect on construction projects. Therefore, the main contribution of current study offers a systematic approach to assessing and managing risks associated with delays in construction projects. By quantifying the likelihood of different delay scenarios, project managers can make informed decisions to mitigate risks and optimize scheduling strategies. The main objective during the construction phases is to complete the project on time and within the budget and meet the set quality requirements and other specifications simultaneously. For this purpose, a framework to identify and prioritize delays and critical activities is proposed in current study and an attempt is made to implement it using the framework introduced in a real case study on the freeway projects of Iran. Accordingly, first, several delays known in free construction projects were considered using the available theoretical resources, they were then subjected to the judgment of experts employing the Delphi technique so 14 delays were identified in the first round of implementing the Delphi technique. Subsequently, a schedule was designed for freeway projects consisting of 13 activities. In the continuation of this research, a questionnaire was prepared to collect information, and 48 answer sheets were carefully completed and received by experts. Then, by running the second round of Delphi, five critical delays were selected among the identified delays, and the statistical delay functions of each of them were estimated using Decision Tools software. Then, by designing 19 scenarios, the effect of each of the critical delays in the activities was reported based on the designed scenarios. Also, for further analysis, nine and five

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scenarios were designed based on the most important delay factors on critical activities and two important activities, respectively; and using the PERT technique, the certain value of increase in activity time was calculated based on different probabilities. According to the reported PERT, the scenarios were prioritized in each step.

**Keyword:** Delay, Critical Activity, Scenario, Delphi Technique, PERT Technique.

## 1 Introduction

The main task of a project manager is to control the completion of the project within the specified time and budget, and according to the requested quality, which is referred to as the critical success factor of the project. If any of the aforementioned does not go as expected, the project will face many problems in the future [1]. The construction process depends on many controllable and uncontrollable variables. Of course, completing a project in a certain time is a sign of the efficiency of the system. Achieving this principle requires mutual and constructive cooperation of those involved in the project, i.e., employers, consultants, contractors, material suppliers, and other stakeholders, and better communication can be established among them by introducing new project management tools in the construction industry [2]. The construction industry is one of the major sectors providing significant components for the development of the economy. However, many projects experience extensive delays. The construction process is exposed to many unpredictable variables and factors, which come from many sources and therefore exceed the initial cost estimate. Because if the construction period is extended, higher loan costs, inflation, and other commercial factors will increase the construction costs, and if the construction costs increase, the project may lack an acceptable and practical performance from an economic point of view. Identifying the delay factors in construction projects is the first step to decreasing this loss. When their causes are identified, delays can be prevented or minimized [3]. According to theoretical sources, the causes of delay are divided into nine main groups, including factors related to the consultant, including poor communication and coordination with other parties, delays in inspection and testing, and delayed preparation and approval of plans, factors related to the employer, including change order, delay in decision making, and delay in payment of status statement, factors related to the contractor, including inexperience of the contractor, re-work due to errors during construction, and poor site management and supervision, factors related to design, including poor design, design errors, project design complexity, factors related to worker, including lack of skilled labor, low productivity of workers, and insufficient skills of equipment operators, factors related to materials and equipment, including lack of equipment, lack of construction materials, frequent equipment failure, external factors, including accidents during construction, natural phenomena, and unfavorable weather conditions, factors related to the project, including awarding the project to the lowest bidder and not having access to the site [4]. These factors are problems that all countries face and generally take place in all construction projects, but their size varies according to the type of project, country, company, and other factors. Simulation is a suitable option to check the performance of such sets whose mechanism we intend to study in the long term [5].

The intention behind conducting of current research is to identify the effect of delays in construction project scheduling is crucial due to the following reasons. For example, construction projects are inherently prone to delays, which can have significant repercussions on project timelines and budgets. By employing Monte Carlo simulation, researchers can quantify the potential impact of delays, thus enabling project managers to proactively identify and mitigate risks. Understanding the effects of delays through simulation allows for better resource allocation and scheduling adjustments. This can lead to improved efficiency in project execution and cost savings by minimizing the disruptions caused by delays. The current research aids decision-makers in making informed choices regarding project scheduling strategies. By simulating various delay scenarios, stakeholders can evaluate the consequences of different decisions and devise effective mitigation plans to maintain project progress. By identifying critical paths and assessing the ripple effects of delays, the research contributes to enhancing overall project performance. This can result in timely project completion, increased stakeholder satisfaction, and reduced likelihood of disputes arising from schedule delays. Finally, a research focusing on Monte Carlo simulation in construction project scheduling has been developed to the body of knowledge in project management. It introduces innovative methodologies for risk assessment and scheduling optimization, ultimately contributing to the advancement of best practices in the construction industry.

According to the above-mentioned, the most important measures taken in this research, the primary contribution of current research lies in the application of Monte Carlo simulation techniques to analyze and quantify the impact of delays on construction project scheduling. By conducting comprehensive simulations based on probabilistic inputs, the study provides valuable insights into the potential effects of delays on project timelines and outcomes. Specifically, the research contributes to the field of construction project management by:

1. **Enhancing Risk Assessment**: Through Monte Carlo simulation, the study offers a systematic approach to assessing and managing risks associated with delays in construction projects. By quantifying the likelihood of different delay scenarios, project managers can make informed decisions to mitigate risks and optimize scheduling strategies.

2. **Improving Decision-Making**: The research equips project stakeholders with a tool to make data-driven decisions regarding project scheduling. By simulating various delay scenarios, decision-makers can better understand the implications of delays and proactively plan for contingencies to minimize disruptions.

3. **Optimizing Project Performance**: By identifying critical paths and analyzing the ripple effects of delays on project timelines, the study helps in optimizing project performance and resource allocation. This can lead to improved efficiency, cost savings, and timely project delivery.

Overall, the research contributes to advancing the understanding of how delays impact construction project scheduling and provides practical insights for enhancing project management practices in the face of uncertainties.

The rest of this paper is organized as follows. In the second section, a historical review of the subject's background is presented. In the third section, the research identification method is provided. In the fourth section, the results of the implementation of the research method are presented. Finally, in the fifth section, a general conclusion is provided along with future suggestions for research.



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## 2 Literature review

In the field of construction project literature, various studies have been conducted on the key effective factors and the delays concerning them. For example, Kikwasi [3] pointed out the handover of projects through holding tenders at the minimum price, changes in design, difficulty in financing, delay in payment of status statement to the contractor, delay in transfer of information, and non-acceptance of the work done by the monitoring body as the most important reasons for delay in construction projects. Shebob et al. [4] carried out a study on the most important reasons for delays in construction projects, which are as follows: changes in the scope of the project, delay in payment of status statements, poor coordination and communication between the consultant and other departments, changes in the price of materials, adverse weather conditions in the site environment, and economic problems. Dengiz et al. [6] believe that rework in the implementation phase, changes in design by the employer and consultant during implementation, unskilled labor, waiting for access to work teams, and price fluctuations are the most important. The reasons for the delay are in the construction projects. The study of Kim and Tuan [7] showed that the lack of ability of the employer, consultant, designer, contractor, and monitoring system is the most important reason for delays in construction projects. Shah [8] conducted a study on the comparison of the most important reasons for delays in construction projects in Australia, Ghana, and Malaysia. According to this research, the most important reasons for delays in construction projects in Australia are improper planning and scheduling, improper construction methods, and not paying attention to the importance of the effect of project control processes; delays in the payment of status statements, unrealistic project cost estimation and project complexity in Ghana; and poor site management, and the contractor's insufficient experience in Malaysia. Emam et al. [9] believe that the delay in decision-making, differences between the general plans and the plans of executive details, the basic changes in the executive details during construction, the delay in addressing the contractor's claims, and the illogicality of the overall project scheduling are the most important reason for the delay in construction projects. Thorat et al. [10] state that the lack of sufficient skills in the workforce, improper planning by the contractor, improper site management by the contractor, delay in payment of status statements by the employer, and insufficient experience of the consultant are the most important reasons for delays in construction projects. Recently, Zhao et al. [11] considered delay prediction in prefabricated projects using a neural network to consider the effects of risk in this type of project. In general, this paper aims to provide a delay prediction model system for construction programs, which can provide key information to control the delay effects of risk-related factors in construction planning. Godarzizad et al. [12] investigated the prediction of construction efficiency using an artificial neural network and Grasshopper optimization algorithm. This paper aims to measure the efficiency of construction and concrete pouring operations related to the construction of commercial-administrative complex projects in Iran. For this purpose, 19 important factors with a significant effect on construction productivity were identified and classified into five groups including personal, managerial, economic, technical, and environmental aspects. Then, a hybrid model based on an artificial neural network (ANN) and grasshopper optimization algorithm (GOA) was presented to determine the most effective factors and increase the accuracy of the constructed model. Ebrahimi et al. [13] proposed an artificial intelligent hybrid model based on a particle optimization planning model to predict productivity and optimize workers. This paper presents a new approach using a hybrid feature using machine learning (ML) and particle swarm optimization (PSO) to predict and optimize construction labor productivity. Kazerooni et al. [14] prioritized



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improvement strategies for construction labor productivity using fuzzy multi-criteria decision-making. This paper proposes a decision support model that prioritizes labor productivity improvement strategies based on their effectiveness using fuzzy multi-criteria decision-making. The proposed model is used as a practical example to determine improvement strategies for labor productivity for concrete pouring activities in construction projects. Ahmed and Alkhamis [15] improved patient delay time by presenting a combined optimization and simulation model in a public hospital in Kuwait. They showed that with the establishment of the optimal combination, the duration of admission of patients in this hospital is significantly reduced. Zolghadr et al. [16] integrated epidemic models with complex networks to explore risk propagation mechanisms in prefabricated building project supply chain (PBPSC). The hierarchical structure of PBPSC was transited into a complex network for analyzing the features of the risk propagation process and the risk propagation capacity of initial infection nodes. The analysis results indicated that risk propagation and risk recovery were medium and often overlooked, which caused risk propagation in PBPSC. When major prefabricated building project contractors and construction enterprises were affected by risks, risk propagation was more likely to occur in PBPSC. Han et al. [17] proposed a new framework for project portfolio selection and constructs a risk propagation model based on strategic objectives to study the impact of risk propagation on substitution in the project portfolio. Bai et al. [18] presented the dynamic risk management of construction project portfolios (CPPs) and improved the effect of risk response. For this purpose, a simulation–optimization model was developed. The model integrated using System Dynamics and optimization to dynamically select risk response strategies (RRSs) and facilitate more refined resource allocation.

Based on the above-mentioned, no study can investigate the effect of delays in the long term while identifying the factors. Therefore, this research is intended to propose a framework that, while identifying the effective delay factors, can assess the effect of each of them in the long run using Monte Carlo simulation with a suitable classification.

## 3 Methods

The proposed framework for conducting this research consists of eight steps. Each of these steps is explained below.

**Step 1: Determine the objective and identify reasons for delay using Delphi**

An objective is generally selected based on the internal performance of the existing problem, system output performance analysis, sensitivity analysis, or even through what-if simulation studies, which are based on this logic [19]. Therefore, through the examination of the existing classified archive documents prepared and arranged by construction experts and road construction project managers, the main reasons for the delay in the intended problem are identified.

After identifying the reason for the delay, their data is prepared from the classified upstream documents to have them at their disposal for the next actions. The most important delays are identified using the Delphi technique and an interview plan with experts.

Delphi is the name of a method in scientific research that was first designed and developed in the late 1950s by the Rand Company for the scientific review of the opinions of experts in the California Army Defense Project, but due to security reasons, it was not published until 12 years later. Its first civilian application was also proposed in economic



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development planning. In general, Delphi has been recognized as an important scientific method since the mid-1960s and is now used for a wide range of future-oriented and complex questions and in a wide range of fields and disciplines. The name of Delphi comes from the Oracle Temple in the ancient Greek city of Delphi, where the Greeks received occult answers from its priests. Some people do not agree with this title because they believe that this method implies a kind of occultism and prophecy. The Delphi method is a systematic and interactive method for forecasting, which relies on the opinions of a panel of independent experts with the premise that group judgment is more valid than individual judgment. In this method, carefully selected experts answer the questionnaires in two or more rounds, and after each round, the program coordinator or manager provides an anonymous summary of the experts' predictions and the respondents' reasons for it. Then, the experts are encouraged to revise their previous answers in the light of the opinions of other members of the board or Delphi group. It is believed that during this process, the answers will be reduced and the Delphi group will be oriented toward the correct answer, and finally, after several repetitions, a consensus will emerge among the Delphi members. The Delphi method is widely used for commercial and business forecasts and predictions. Identification of experts is an important point in Delphi, as the achievement of goals depends on the careful selection of participants. Delphi focuses on extracting opinions from experts in a short time, and the results depend on the expertise of the people in the desired knowledge, the quality and accuracy of the answers, and their continuous cooperation and involvement during the study period. One of the important steps in the Delphi method is reaching a consensus and deciding whether to stop or continue the Delphi courses, which requires a criterion, one of which is Kendall's correlation coefficient. Kendall's correlation coefficient, denoted by the symbol w, is a nonparametric test used to determine the degree of coordination between comments. The Kendall's coefficient varies between 0 and 1. If Kendall's coefficient is zero, it means there is no complete agreement, and if it is one, it means there is complete agreement. Kendall's correlation coefficient can be used to finish the rounds of the Delphi technique. Kendall's coordination coefficient is calculated from Equation (1) below.

$$w = \frac{s}{\frac{1}{12}k^2(N^2-N)} \tag{1}$$

Where $S$ equals the sum of the squares of the deviations of $R_j$ from the mean of $R_j$ and is calculated according to Equation (2).

$$S = \sum[R_{j-} \frac{\sum R_{j-}}{N}]^2 \tag{2}$$

$R_j$ is the sum of the ranks of a factor, $K$ is the number of sets of ranks (number of judges), and $N$ is the number of ranked factors. In this research, five experts were selected to answer the questions, and the experts were selected among the Delphi participants, with the feature that the answering team at this stage has a higher level of knowledge and expertise in the main field. The research found that in the field of road construction, each of the senior managers of various departments related to road construction projects had work experience, which had a high level of education, expertise, and experience in this regard, and had sufficient information about other parts of the project as well. The details of the experts' records are listed in Table 1.

**Step 2: Form a schedule**

At this stage, with the help of experts working in the road industry and theoretical resources, a schedule consisting of 13 activities is formed. Using this schedule and drawing the Gantt chart related to the duration of the project, the start and end date and the prerequisites of each activity are identified. Then, the critical path of the project can also be identified using MSP software. Naturally, knowing the critical path that takes the most time to complete the process can help in the progress of this project. For this reason, this step is considered in the proposed framework.

**Table 1** Details of participants

| Row | Age (yrs.) | | | Education | | | Experience (yrs.) | | | Organizational position |
|---|---|---|---|---|---|---|---|---|---|---|
| | 25 to 30 | 30 to 35 | 35 to 40 | Bachelor | Master | Ph.D. | > 5 | > 10 | > 15 | |
| Expert 1 | * | | | | | * | | * | | CEO |
| Expert 2 | * | | | | * | | * | | | Project manager |
| Expert 3 | | * | | | * | | | | * | Project manager |
| Expert 4 | | | * | * | | | | * | | Project manager |
| Expert 5 | | | * | | * | | | | * | CEO |

**Step 3: Create a questionnaire**

At this stage, a questionnaire based on all identified delays is prepared to collect information from experts working in the field of road construction. In this questionnaire, 14 delays are subjected to pairwise comparison with 13 identified activities. Based on the data collected from the experts, the scores obtained for each activity-delay pairwise comparison are numbered in the range of 0 to 500.

**Step 4: Determine the distribution functions of the identified delays**

In this step, the graph of distribution functions of all 14 identified delays is estimated using Decision Tools software. Considering this section, in fact, by estimating the statistical distribution functions of each of the delays (both critical and non-critical) using the collected data, the effect of each delay on the progress of the project is determined. Then, those distribution functions related to critical delays are simulated in the Decision Tools program using the scenarios defined in the next step.

**Step 5: Determine the scenario**

At this stage, by identifying critical activities and critical delays, 19 scenarios are designed, and these scenarios are considered as examples of test designs for the input of a simulation model.

**Step 6: Simulation**

At this stage, the simulation and the effect of the delay on the entire project time are examined in the probabilities of 70%, 80%, and 90%. Then, the results for each of the considered probabilities for each scenario are reported. For this purpose, implementing distribution functions in each of the scenarios, using Monte Carlo simulation, we check the time increase in each scenario compared to the existing situation because simulation is primarily a method of generating data on a real phenomenon that follows a statistical distribution. Although the simulated data may not exactly match the reality, when access to the information and data of a phenomenon is very expensive and time-consuming, simulation is a successful and especially cost-effective way to study such phenomena. However, the Monte Carlo method, which is used to study physical and economic systems, uses the iteration of simulation to understand the behavior of a phenomenon. Therefore, the more the number of iterations in the simulation for the Monte Carlo method, the more reliable the results will be. One of the characteristics of the Monte Carlo method is to keep suitable data and eliminate unsuitable data. Although the Monte Carlo method has different modes, the following steps can usually be considered for it:

1. Specifying the characteristics of the input data,
2. Input, values as simulated random data,
3. Performing calculations on generated random numbers,
4. Determining acceptance and rejection points as a result of simulation,
5. Summarizing and finalizing the calculations to access the answer to the main question.

**Step 7: Repeat Steps 5 and 6**

At this stage, by repeating the fifth step (scenario determination), we update the relevant information for the most important delay factors on critical activities, as well as delay factors on two types of important activities, and estimate the required probabilities.

**Step 8: PERT technique**

In this step, by using the program evaluation review technique (PERT) technique, a certain value is determined for the interval values of each of the considered probabilities in each scenario formed in Steps 5 and 7. This step can be calculated using the formula of the PERT technique according to Equation (3).

$$\frac{min_{\text{interval}}+4(mean)+max_{\text{interval}}}{6} \tag{3}$$

Equation (3) is used to calculate probabilities of 70%, 80%, and 90%. From this equation, to convert the created time intervals into a number so that we can show the value of the increase in each of the scenarios in the graph, the PERT technique is used for calculation. Figure 1 illustrates the research stages.

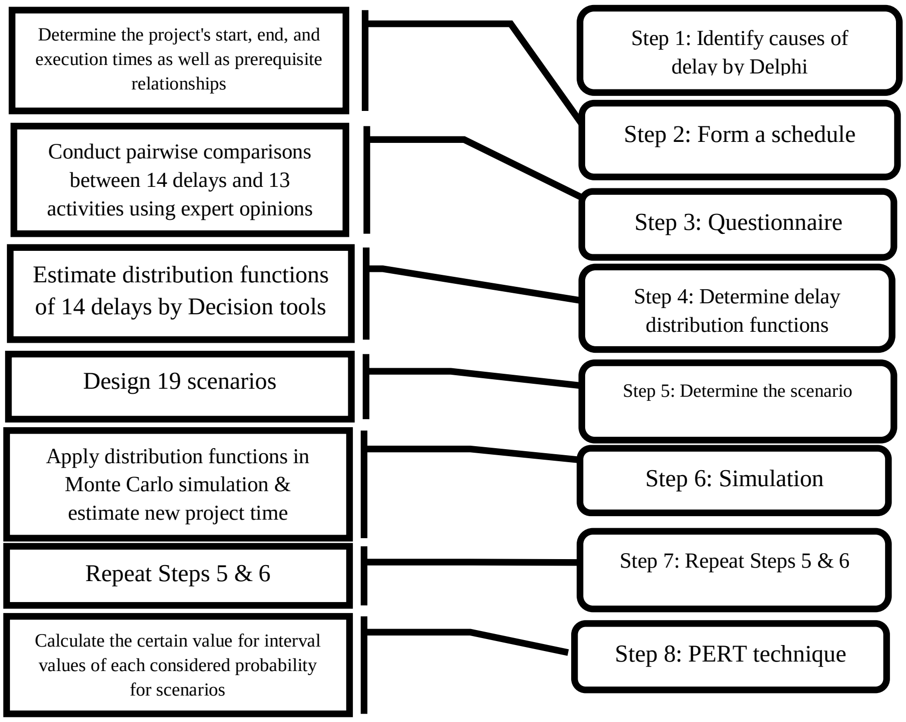


**Fig. 1** Conceptual model of the research method


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## 4 Results

In this research, library studies and the Delphi technique were used in two rounds to identify important delays. In general, studying theoretical sources, several delays were identified, after sharing them among five experts, according to the Delphi technique, 14 delays were identified based on the opinions of Delphi experts. Information on the experts is shown in Table 1. Accordingly, in 27 road construction projects in the country, the required data for 14 identified delays were collected based on classified archive documents, whose information is listed in Table 2. These are the obvious delays of the contracting companies that are responsible for the maintenance and repair of the country's freeways at every stage.

### 4.1 Scheduling

Scheduling for construction projects such as road construction projects is carried out to specify the work steps and the time required for each step. The existence of a schedule reduces the occurrence of critical activities in the project. In project scheduling for civil works, a work calendar is defined to determine what work needs to be done and what is the priority of each work. Defining a seasonal calendar helps to determine how much the project should progress in each season and how work should proceed. It is also important to define the workshop calendar in building scheduling, as it accelerates workshop work and organizes the project. Defining work calendars for each activity helps to define work efficiency well and increase project efficiency. Scheduling in this research is done with the advanced MSP software or Microsoft Project Management. Microsoft Project Management software helps to draw a network diagram based on the project scheduling and makes the work more accurate. The scheduling considered for road construction projects in this research is according to Table 3.

The schedule table (3), in project management, shows a list of project milestones, activities, and deliverables, with start and end dates for the activities, prerequisites, and duration of activities. The schedule displayed in Figure 2, as well as the order of project activities from the beginning of the work to the end of the project, are important factors in determining the work method. In the explanation of Figure 2, it is necessary to mention that the activities in red are the critical ones that we have reached this conclusion using the MSP software. Also, by drawing the Gantt chart, these activities are colored red.

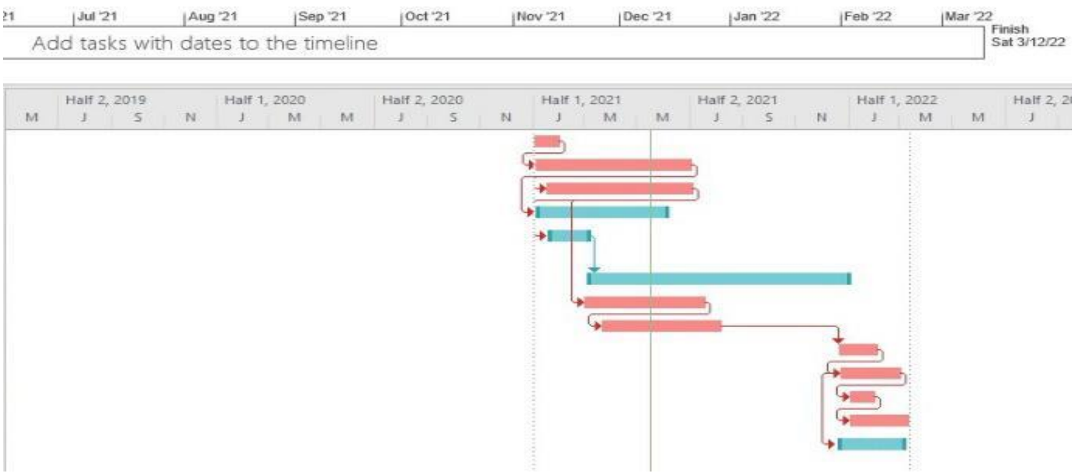


**Fig. 2** Gantt chart of road construction scheduling



[ DOI: 10.71885/ijorlu-2024-1-665 ]

**Table 2** Data related to road construction companies

| Delay factor / Project | Assessment-related problems (T1) | Presence of utility interference (T2) | Credit and allocation problems (T3) | Problems related to the supply of materials and their shortage (T4) | Lack of access to projected mines (T5) | Effect on notification of plans and specifications (T6) | Change in design, etc. (T7) | Prevention of local organizations (T8) | Predicted events (T9) | Force majeure events (T10) | Problems of fuel supply restrictions (T11) | Problems of flammable materials (T12) | Other cases (T13) | Weather conditions (T14) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Urmia-Tabriz | 0 | 20 | 0 | 30 | 30 | 0 | 306 | 0 | 0 | 0 | 0 | 0 | 85 | 0 |
| Plot 4, Urmia, Tabriz | 455 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Plot 1, Tehran, Tabriz | 1500 | 365 | 730 | 365 | 150 | 0 | 180 | 730 | 730 | 0 | 0 | 0 | 0 | 0 |
| Plot 2, Tehran Pardis (A) | 723 | 406 | 723 | 406 | 200 | 0 | 406 | 812 | 111 | 0 | 180 | 180 | 450 | 240 |
| Plot 2, Tehran Pardis (B) | 0 | 279 | 753 | 377 | 377 | 0 | 31 | 0 | 0 | 0 | 300 | 0 | 67 | 267 |
| Complementarity of Tehran Pardis | 399 | 295 | 797 | 399 | 399 | 0 | 196 | 797 | 0 | 0 | 399 | 164 | 262 | 262 |
| Plots 3 & 4, Tehran Pardis | 0 | 157 | 0 | 0 | 0 | 114 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Plots 2 & 3, shrine to shrine | 1009 | 0 | 0 | 0 | 0 | 0 | 0 | 1009 | 0 | 0 | 0 | 0 | 0 | 177 |
| Plot 1, Zanjan Tabriz | 681 | 681 | 584 | 156 | 0 | 29 | 87 | 175 | 0 | 0 | 175 | 0 | 0 | 175 |
| Complementary of plot 1, Zanjan Tabriz | 59 | 23 | 0 | 0 | 35 | 53 | 0 | 0 | 0 | 0 | 0 | 0 | 18 | 118 |
| Plot 5, Zanjan Tabriz | 300 | 128 | 39 | 171 | 165 | 0 | 0 | 86 | 0 | 0 | 0 | 0 | 469 | 0 |
| Plot 5, complementary of Zanjan Tabriz | 364 | 179 | 90 | 45 | 30 | 0 | 0 | 20 | 20 | 0 | 0 | 0 | 0 | 16 |
| Plot 6, Zanjan Tabriz | 25 | 38 | 1845 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 770 | 101 |
| Plot 9, Zanjan Tabriz | 7 | 0 | 137 | 0 | 0 | 0 | 14 | 0 | 0 | 0 | 11 | 0 | 0 | 0 |
| Plot 10, Zanjan Tabriz | 56 | 56 | 184 | 56 | 37 | 0 | 0 | 0 | 0 | 0 | 167 | 0 | 0 | 84 |
| Ventilation of Zanjan Tabriz | 0 | 0 | 228 | 0 | 0 | 0 | 0 | 174 | 0 | 0 | 0 | 0 | 0 | 32 |
| Plot 1 Qazvin Rasht (A) | 1200 | 360 | 0 | 200 | 50 | 0 | 0 | 700 | 60 | 360 | 30 | 0 | 0 | 25 |
| Plots 1 & 2 Qazvin Rasht (A) | 0 | 0 | 0 | 18 | 0 | 41 | 63 | 0 | 0 | 0 | 0 | 0 | 0 | 18 |
| Plots 2 & 3 Qazvin Rasht (A) | 0 | 0 | 45 | 67 | 0 | 0 | 210 | 0 | 165 | 0 | 0 | 0 | 15 | 22 |
| Plots 3 & 4 Qazvin Rasht (A) | 250 | 50 | 200 | 0 | 0 | 0 | 100 | 0 | 0 | 0 | 0 | 0 | 25 | 0 |
| Plots 2 & 3 Qazvin Rasht (B) | 0 | 0 | 0 | 365 | 0 | 0 | 365 | 0 | 0 | 0 | 0 | 0 | 214 | 0 |
| Guardrail of Qazvin Rasht | 608 | 195 | 441 | 0 | 0 | 150 | 50 | 0 | 0 | 0 | 0 | 0 | 15 | 11 |
| Plot 1, Maragheh Hashtroud | 132 | 0 | 498 | 0 | 0 | 82 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Plot 2, Maragheh Hashtroud | 403 | 300 | 394 | 0 | 300 | 180 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 93 |
| Plot 3, Maragheh Hashtroud | 240 | 0 | 220 | 0 | 0 | 180 | 160 | 0 | 0 | 0 | 0 | 0 | 0 | 105 |
| Plots 2 & 3, Hemat Karaj | 180 | 30 | 0 | 0 | 0 | 0 | 272 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 3** Road construction project scheduling

| Activity name | Duration of activity | Start date | End date | Prerequisites |
|---|---|---|---|---|
| Implementation and nailing | 30 | 01/01/2021 | 01/31/2021 | |
| Excavation | 180 | 01/04/2021 | 07/03/2021 | 1FS-27 |
| Leveling | 170 | 01/16/2021 | 07/05/2021 | 2FS-168 |
| Embankment | 150 | 01/06/2021 | 06/05/2021 | 2FS-178 |
| Excavation for bridges and roads | 45 | 01/20/2021 | 03/06/2021 | 3FS-166 |
| Implementation of bridges and canals | 300 | 03/07/2021 | 01/01/2022 | 5FS+1 |
| Implementation of sub-base | 140 | 03/01/2021 | 07/19/2021 | 3FS-126 |
| Implementation of base | 140 | 03/20/2021 | 08/07/2021 | 7FS-121 |
| Implementation of prime coat-bituminous coating | 45 | 12/20/2021 | 02/03/2022 | 8FS+135 |
| Implementation of asphalt binder | 70 | 12/22/2021 | 03/02/2022 | 9FS-43 |
| Implementation of single coat -bituminous coating | 30 | 01/01/2022 | 01/31/2022 | 10FS-60 |
| Implementation of Topeka asphalt (wearing course) | 70 | 01/02/2022 | 03/13/2022 | 11FS-29 |
| Installation of guardrail | 75 | 12/21/2021 | 03/06/2022 | 10SS-1 |
| Total project time | 436 | | | |

### 4.2. Determining the statistical distribution functions of effective delays

In this section, a questionnaire based on all identified delays was prepared to collect information from experts working in the field of road construction. By performing the second round of Delphi, five frequent and most important delays are selected from them. The most important critical delays based on the implementation of the second round of Delphi are shown in Table 4.



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**Table 4.** Identified critical delays based on the implementation of the second round of Delphi

| ID | Reasons for delay extracted from the 2nd Delphi according to experts |
|---|---|
| T1 | Assessment-related problems to evaluation (no evaluation, no release, etc.) |
| T2 | Presence of utility interference (power transmission, gas, telephone, water, etc.) |
| T3 | Credit and allocation problems |
| T7 | Changes in design, work volumes, and new works (variants, longitudinal profile, etc.) |
| T14 | Weather conditions |

Then, we estimate the most suitable distribution function for each critical activity concerning each frequent delay considered in the second round of Delphi based on their delay time using Decision Tools software. Tables 5 to 9 show the results related to the estimation of the distribution function of frequent delays.

**Table 5** Summary of statistical information on T1 delay

| Delay | Activity | Statistical distribution |
|---|---|---|
| Assessment-related problems (T1) | Implementation and nailing | Risk Uniform (-10.638;510.64) |
| | Excavation | Risk Normal (312.50;153.09) |
| | Leveling | Risk Uniform (-10.638;510.64) |
| | Implementation of sub-base | Risk Uniform (-10.638;510.64) |
| | Implementation of base | Risk Uniform (-10.638;510.64) |
| | Implementation of prime coat-bituminous coating | Risk Triang (0; 0; 615.19) |
| | Implementation of asphalt binder | Risk Uniform (-10.638;510.64) |
| | Implementation of single coat - bituminous coating | Risk Expon (189.38; RiskShift(-3.9453)) |
| | Topeka asphalt | Risk Uniform (-10.638;510.64) |



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**Table 6** Summary of statistical information on T2 delay

| Delay | Activity | Statistical distribution |
|---|---|---|
| Presence of utility interference (T2) | Implementation and nailing | Risk Triang (0; 0; 569.80) |
| | Excavation | Risk Uniform (91.489; 508.51) |
| | Leveling | Risk Uniform (-10.638; 510.64) |
| | Implementation of sub-base | Risk Expon (202.19; RiskShift(-4.2122)) |
| | Implementation of base | Risk Uniform (-10.638; 510.64) |
| | Implementation of prime coat-bituminous coating | Risk Triang (0; 0; 543.76) |
| | Implementation of asphalt binder | Risk Triang (0; 0; 544.98) |
| | Implementation of single coat - bituminous coating | Risk Expon (144.0 6;RiskShift(-3.0013)) |
| | Topeka asphalt | Risk Triang (0; 0; 542.69) |

**Table 7** Summary of statistical information on T3 delay

| Delay | Activity | Statistical distribution |
|---|---|---|
| Credit and allocation problems (T3) | Implementation and nailing | Risk Triang (0; 0; 602.65) |
| | Excavation | Risk Uniform (-10.638; 510.64) |
| | Leveling | Risk Uniform (-10.638; 510.64) |
| | Implementation of sub-base | Risk Triang (-70.779; 500; 500) |
| | Implementation of base | Risk Triang (-25.393; 500; 500) |
| | Implementation of prime coat-bituminous coating | Risk Triang (-32.281; 500; 500) |
| | Implementation of asphalt binder | Risk Pert (-313.39; 500; 500) |
| | Implementation of single coat - bituminous coating | Risk Triang (-36.131; 500; 500) |
| | Topeka asphalt | Risk Pert (-313.39; 500; 500) |



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**Table 8** Summary of statistical information on T7 delay

| Delay | Activity | Statistical distribution |
|---|---|---|
| Changes in design (T7) | Implementation and nailing | Risk Uniform (-10.638; 510.64) |
| | Excavation | Risk Uniform (40.426; 509.7) |
| | Leveling | Risk Triang (0; 0; 614.64) |
| | Implementation of sub-base | Risk Uniform (40.426; 509.57) |
| | Implementation of base | Risk Triang (50; 50; 593.87) |
| | Implementation of prime coat-bituminous coating | Risk Triang (-17.803; 50; 561.60) |
| | Implementation of asphalt binder | Risk Triang (0; 0; 559.86) |
| | Implementation of single coat - bituminous coating | Risk Triang (0; 0; 562.49) |
| | Topeka asphalt | Risk Triang (0; 0; 548.84) |

**Table 9** Summary of statistical information on T14 delay

| Delay | Activity | Statistical distribution |
|---|---|---|
| Changes in design (T14) | Implementation and nailing | RiskLognorm (87.179; 164.20; RiskShift(-3.2581)) |
| | Excavation | RiskExpon (123.72; RiskShift(-2.6324)) |
| | Leveling | RiskExpon (111.15; RiskShift(-2.3155)) |
| | Implementation of sub-base | RiskExpon (129.48; RiskShift(-2.3025)) |
| | Implementation of base | RiskFatigueLife (-1.7097;85.712;1.2307) |
| | Implementation of prime coat-bituminous coating | RiskFatigueLife (-5.1200;94.634;1.2403) |
| | Implementation of asphalt binder | RiskFatigueLife (-6.5650;99.090;1.960) |
| | Implementation of single coat - bituminous coating | RiskFatigueLife (-7.6325;100.05;1.150) |
| | Topeka asphalt | RiskExpon (163.65; RiskShift(1.5907)) |

The estimated probability distribution functions for these delays can be used in future projects and uncertainty can be introduced into the schedules. Finally, by designing scenarios, delays are used in different activities that are on the critical path to check the effect of each of them on freeway activities.

### 4.3 Scenario-based analysis of the effect of delays on the schedule

In this section, the effect of each delay is analyzed based on the proposed scenarios. Also, the percentage of increase in project time according to the scenarios for all four investigated modes with probabilities (70%-80%-90%) is calculated using simulation and the most critical scenario is prioritized for each mode. 19 general scenarios are described as research scenarios, which are as follows:



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- Simulating the effect of the delay of assessment-assessment problems (no assessment, no release, etc.) during excavation, implementation and nailing activities, and implementation of the base
- Simulating the effect of delay (credit and allocation problems) during the activities of asphalt binder implementation, implementation of Topeka asphalt, and the base.
- Simulating the effect of delay (presence of utility interference (power transmission, gas, telephone, water, etc.) during excavation activities, implementation of the base, and levelling
- Simulating the effect of delay (changes in design, work volumes, and new works (variants, longitudinal profile, etc.)) during excavation activities, implementation, and nailing of the route and execution of the sub-base.
- Simulating the effect of delay (weather conditions) during Topeka asphalt implementation activities, asphalt binder implementation, and prime and bituminous coating implementation.
- Simulating the effect of delay (assessment-related problems (no assessment, no release, etc.)) during the excavation activity, the effect of delay (credit and allocation problems) during the asphalt binder execution activity, the effect of delay (existence of utility interference (power transmission), gas, telephone, water, etc.)) During the levelling activity, the effect of delay (weather conditions) during the Topeka asphalt implementation activity and the effect of delay (change in design, work volumes, and new works (variants, longitudinal profile, etc.) during the activity of the sub-base implementation.
- Simulating the effect of delay (assessment-related problems (no assessment, no release, etc.)) during the base implementation activity, the effect of delay (credit and allocation problems) during Topeka asphalt implementation activity, the effect of delay (presence of utility interference (transfer power, gas, telephone, water, etc.)) during the excavation activity, the effect of delay (weather conditions) during the asphalt binder execution activity and the effect of delay (change in design, work volumes, and new works (variants, longitudinal profile, etc.)) During the implementation and nailing activity.
- • Simulating the effect of delay (assessment-related problems (no assessment, no release, etc.)) during the implementation and nailing of the route, the effect of delay (credit and allocation problems) during the activity of asphalt binder, the effect of delay (presence of utility interference (power transmission, gas, telephone, water, etc.)) during the levelling activity, the effect of delay (weather conditions) during the activity of prime and bituminous coating and the effect of delay (change in design, work volumes, and new works (variants, longitudinal profile and...)) during excavation activity.
- Simulating the effect of delay (assessment-related problems (no assessment, no release, etc.)) during excavation activity and the effect of delay (credit and allocation problems) during asphalt binder implementation activity.
- Simulating the effect of delay (assessment-related problems (no assessment, no release, etc.)) during excavation activity and the effect of delay (presence of utility interference (power transmission, gas, telephone, water, etc.)) during activity levelling
- The effect of delay (credit and allocation problems) during the asphalt binder implementation activity and the effect of delay (existence of utility interference (power transmission, gas, telephone, water, etc.)) during the excavation activity.


[ DOI: 10.71885/ijorlu-2024-1-665 ]

- Simulating the effect of delay (assessment-related problems (no assessment, no release, etc.)) during excavation activity and the effect of delay (weather conditions) during Topeka asphalt implementation activity.
- The effect of delay (presence of utility interference (power transmission, gas, telephone, water, etc.)) during the levelling activity and the effect of delay (change in design, work volumes, and new works (variants, longitudinal profile, etc.)) during the sub-base implementation activity.
- Simulating the effect of delay (assessment-related problems (no assessment, no release, etc.)) during excavation activity and the effect of delay (changes in design, work volumes, and new works (variants, longitudinal profile, etc.)) during the base implementation activity.
- The effect of delay (credit and allocation problems) during the asphalt binder implementation activity and the effect of delay (change in design, work volumes, and new works (variants, longitudinal profile, etc.)) during the excavation activity.
- The effect of delay (credit and allocation problems) during the Binder asphalt implementation activity and the effect of delay (weather conditions) during the Topeka asphalt implementation activity.
- The effect of delay (presence of utility interference (power transmission, gas, telephone, water, etc.)) during excavation activity and the effect of delay (weather conditions) during the Topeka asphalt implementation activity.
- The effect of the most critical delay of each activity on the project completion time.
- The effect of the second critical delay of each activity on the project completion time.

The results of investigating the time increase based on 19 critical scenarios with probabilities (70%-80%-90%) are given in Table 10.

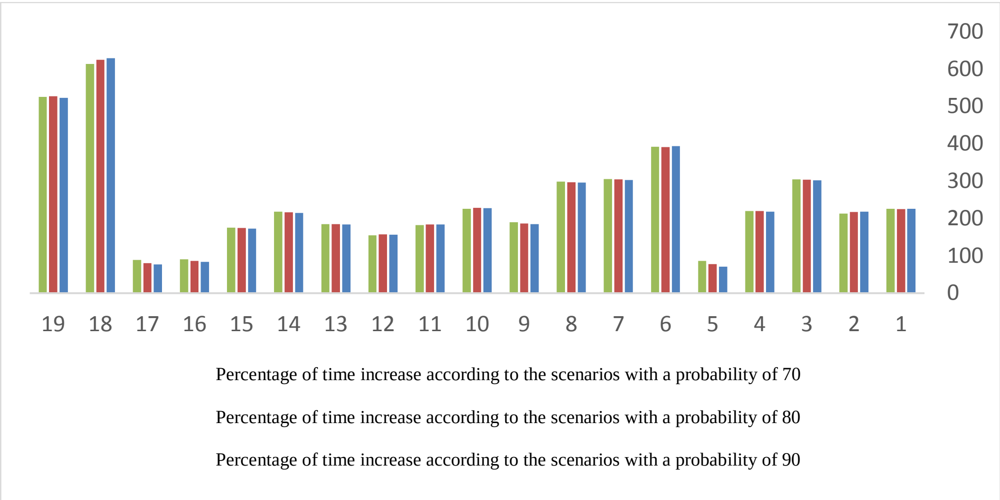


**Fig. 3** Comparison of different probabilities of 19 scenarios

Based on the results of Table 10 in Figure 3, the scenarios are sorted according to the priority of criticality. Each scenario is shown based on the percentage of time increase in Table 10 related to 19 scenarios. Based on the result obtained from the PERT method for different probabilities, the 18th scenario is the most critical.



[ DOI: 10.71885/ijorlu-2024-1-665 ]

**Table 10** Time increase of 19 scenarios with 70, 80, and 90% probabilities using PERT

| Scenario | Percentage of time increase according to the scenarios with a probability of 70 | Percentage of time increase according to the scenarios with a probability of 80 | Percentage of time increase according to the scenarios with a probability of 90 |
|---|---|---|---|
| 18 | 629 | 624.5 | 613 |
| 19 | 523 | 526.5 | 525.5 |
| 6 | 393 | 391 | 392 |
| 7 | 302.5 | 304.5 | 305 |
| 3 | 302 | 303.5 | 304 |
| 8 | 295.5 | 296.5 | 298.5 |
| 10 | 227 | 228 | 226 |
| 1 | 226 | 225 | 226 |
| 4 | 218 | 220 | 219.5 |
| 14 | 215 | 216 | 218 |
| 2 | 218 | 217.5 | 213 |
| 9 | 184.5 | 186 | 189.5 |
| 13 | 184 | 184.5 | 185 |
| 11 | 184 | 184 | 182 |
| 15 | 172.5 | 174 | 175 |
| 12 | 156.5 | 157.5 | 155 |
| 16 | 84 | 86.5 | 90.5 |
| 17 | 77 | 80.5 | 88.5 |
| 5 | 71 | 78 | 86 |

In the following, the second mode of research is related to the estimation of the value of time increase of nine scenarios which are prepared and adjusted based on the most important delay factor for all critical activities. Nine scenarios based on the most important delay factors are prepared as follows:

- Simulating the effect of delay of credit and allocation problems during the implementation and nailing of the route.
- Simulating the effect of delay of credit and allocation problems during the excavation activity.
- Simulating the effect of delay of credit and allocation problems during the leveling activity.
- Simulating the effect of delay of credit and allocation problems during the sub-base implementation.
- Simulating the effect of delay of credit and allocation problems during the base implementation activity.
- Simulating the effect of delay of credit and allocation problems during the primer–bituminous coating activity.
- Simulating the effect of delay of credit and allocation problems during the asphalt binder implementation activity.



[ DOI: 10.71885/ijorlu-2024-1-665 ]

- Simulating the effect of the delay of credit and allocation problems during the implementation of single-coat-bituminous coating.
- Simulating the effect of delay of credit and allocation problems during Topeka asphalt implementation activity.

The results of investigating the time increase based on nine critical scenarios for the most important delay factor with probabilities (70%-80%-90%) are shown in Table 11.

**Table 11** Time increase of nine scenarios related to the allocation credit activity with probabilities of 70, 80, and 90% using PERT

| Scenario | Percentage of time increase according to the scenarios with a probability of 70 | Percentage of time increase according to the scenarios with a probability of 80 | Percentage of time increase according to the scenarios with a probability of 90 |
|---|---|---|---|
| 2 | 103 | 103 | 103 |
| 3 | 97 | 97.5 | 97.5 |
| 5 | 102.5 | 98.5 | 93 |
| 4 | 97 | 93 | 87 |
| 7 | 57.5 | 54.5 | 50 |
| 9 | 57 | 54 | 49.5 |
| 6 | 32.5 | 31.5 | 29.5 |
| 8 | 21.5 | 20.5 | 19.5 |
| 1 | 14 | 15 | 16.5 |

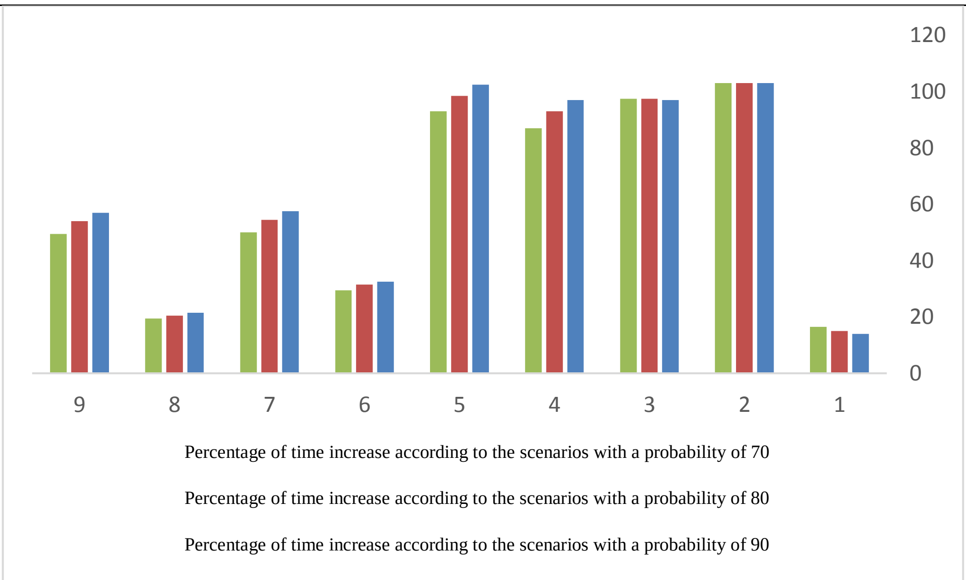


**Fig. 4** Comparison of different probabilities of nine scenarios

In Figure 4, the scenarios are sorted according to the priority of criticality. Each scenario is shown based on the percentage of time increase in Table 11 related to 9 different scenarios. Based on the result obtained from the PERT method for different probabilities, the second scenario (simulating the



[ DOI: 10.71885/ijorlu-2024-1-665 ]

effect of delay of credit and allocation problems during the excavation activity) is the most critical. The third mode of investigating the scenarios considered in this research is related to the estimation of the value of time increase of nine scenarios which are prepared and adjusted based on the most important delay factor for all critical activities. Nine scenarios based on the most important delay factors are prepared as follows:

- Simulating the effect of the delay of assessment-related problems (no assessment, no release, etc.) during the base activity.
- Simulating the effect of the delay of the presence of utility interference (power transmission, gas, telephone, water, etc.) during the base activity.
- Simulating the effect of delay of credit and allocation problems during the base activity.
- Simulating the effect of the delay of changes in the design, work volumes, and new works (variants, longitudinal profile, etc.) during the base activity.
- Simulating the effect of delay of weather conditions during the base activity.

The results of investigating the time increase based on five critical scenarios for the most important delay factor with probabilities (70%-80%-90%) are shown in Table 12.

**Table 12** Time increase of five scenarios related to the base activity with probabilities of 70, 80, and 90% using PERT

| Scenario | Percentage of time increase according to the scenarios with a probability of 70 | Percentage of time increase according to the scenarios with a probability of 80 | Percentage of time increase according to the scenarios with a probability of 90 |
|---|---|---|---|
| 3 | 102 | 98.5 | 93 |
| 4 | 76.5 | 80 | 85.5 |
| 2 | 80.5 | 80 | 80 |
| 1 | 80.5 | 80 | 80 |
| 5 | 46.5 | 54.5 | 68.5 |



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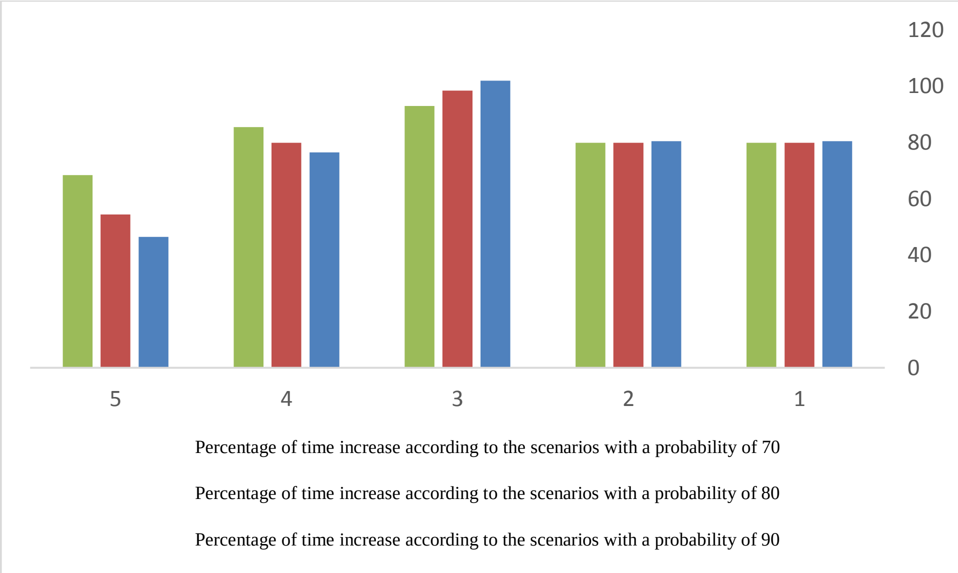


**Fig. 5** Comparison of different probabilities of five scenarios related to base

In Figure 5, the scenarios are sorted according to the priority of criticality. Each scenario is shown based on the percentage of time increase in Table 11 related to 9 different scenarios. Based on the result obtained from the PERT method for different probabilities, the third scenario (simulating the effect of delay of credit and allocation problems during the base activity) is the most critical. Finally, in the fourth mode of investigating the scenarios considered in this research, the time increase of five scenarios, which are prepared and adjusted based on one of the most important delay factors, i.e., excavation, is studied. Nine scenarios based on the most important delay factors are prepared as follows:

- Simulating the effect of the delay of assessment-related problems (no assessment, no release, etc.) during the excavation activity.
- Simulating the effect of the delay of the presence of utility interference (power transmission, gas, telephone, water, etc.) during the excavation activity.
- Simulating the effect of delay of credit and allocation problems during the excavation activity.
- Simulating the effect of delay of changes in the design, work volumes, and new works (variants, longitudinal profile, etc.) during the excavation activity.
- Simulating the effect of delay of weather conditions during the excavation activity.

The results of investigating the time increase based on five critical scenarios for the most important delay factor on the excavation activity with probabilities (70%-80%-90%) are shown in Table 13.

In Figure 6, the scenarios are sorted according to the priority of criticality. Each scenario is shown based on the percentage of time increase in tables related to different scenarios. Based on the result obtained from the PERT method for different probabilities, the first scenario (simulating the effect of delay of assessment-related problems (no assessment, no release, etc.) during the excavation activity) is the most critical.



[ DOI: 10.71885/ijorlu-2024-1-665 ]

**Table 13** Time increase of five scenarios related to the excavation activity with probabilities of 70, 80, and 90% using PERT

| Scenario | Percentage of time increase according to the scenarios with a probability of 70 | Percentage of time increase according to the scenarios with a probability of 80 | Percentage of time increase according to the scenarios with a probability of 90 |
|---|---|---|---|
| 1 | 128.5 | 129 | 129 |
| 2 | 123.5 | 123.5 | 123.5 |
| 4 | 113.5 | 113.5 | 113 |
| 3 | 1.3 | 1.3 | 103 |
| 5 | 52.5 | 61.5 | 52.5 |

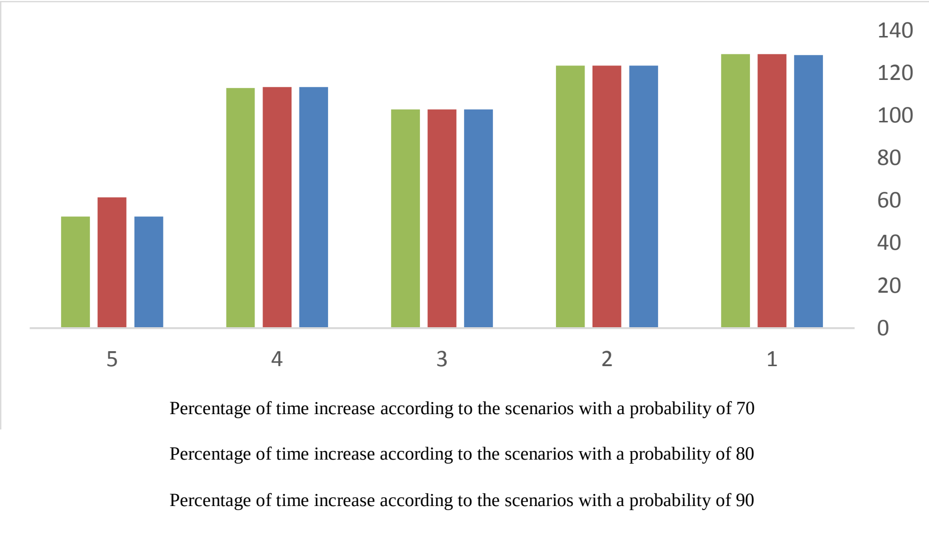


**Fig. 6** Comparison of different probabilities of five scenarios related to excavation

## 5 Conclusion

Delay in construction projects, including a high-rise apartment, house building, or road repair, is one of the frequent problems in the construction industry and creates major concerns for project performance. These problems encompass project completion delays, cost increases, work disruptions, loss of productivity, third-party claims, disputes, and contract abandonment or termination. The reasons for these delays are different from unnatural phenomena to bad weather, lack of materials, site conditions, and work disputes, and only a few of them have been mentioned. Additionally, the analysis of delays is more associated with the fact that the causes of delays are often multifaceted. From the introduction of the concept of time to the completion date of the projects, delays have been met in the construction process. The most important aspect of delay analysis is to find the cause of the delay affecting the critical path and the completion time of the project. Identifying the cause of delays can be a difficult task and depends on the scale of the project and the availability of construction records. Therefore, it is necessary to record the data related to daily progress so that the responsibility for the delay is known and damage estimation can be done accurately with less difference in the relevant departments. Hence, it is essential to use management software. Thus, in this research, a simulation-based framework was proposed to answer the problem of scheduling construction projects in a real example of Iran's freeways. Accordingly, it is possible to measure the effect of each delay on the duration of the projects while identifying the reasons for the delay. In this paper, by reviewing the literature, it was done separately in the main areas of research, i.e., the effect of delays in the scheduling of construction projects. Given that the effect of simulation and delay was the main topic of this research, it was done regarding the types of methods and the classification of the papers in it to identify the research gap in the research literature. Then, a practical method for analyzing and solving the problem was introduced. The main idea of the proposed method is to be able to pay attention to different dimensions of the problem. Therefore, according to the proposed method, important delays were first identified using the Delphi technique, and then critical delays were selected among them by performing the second round of Delphi. Then, we estimated the distribution function of important delays identified in the second round of Delphi based on their delay duration, and finally, by designing scenarios, we applied the delays in different activities to use each of the proposed scenarios to investigate the effect of each of the factors on the project implementation time. Practical implications for project stakeholders and the construction industry as a whole: project managers can use the findings from Monte Carlo simulations to proactively identify and mitigate potential risks associated with delays in construction projects. This enables better risk management practices and improves the overall resilience of project schedules. Stakeholders can make more informed decisions regarding project scheduling by leveraging the insights gained from simulation analyses. Understanding the effects of delays allows for the implementation of effective contingency plans and adjustments to project timelines to minimize disruptions. By simulating delay scenarios, project teams can optimize the allocation of resources, labor, and materials to maintain project progress in the face of uncertainties. This leads to cost savings, increased efficiency, and better utilization of project resources. The research facilitates the identification of critical paths and potential bottlenecks that may arise due to delays. By addressing these issues proactively, project teams can ensure timely project delivery and meet stakeholder expectations regarding project completion. One of the main limitations of conducting research on using Monte Carlo simulation to analyze the effect of delays in construction project scheduling is the reliance on assumptions and input data accuracy. The accuracy of the simulation results heavily depends on the quality and reliability of the data and assumptions used in the simulation model. The most important suggestions for future research are: using other methods to calculate the weight and importance of delays such as the Eigenvector technique and compare with the results obtained in this research, using other decision-making methods such as TOPSIS for prioritization of construction projects, using fuzzy logic and involving the uncertainty issues during problem solving and planning.

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