

Airvehicle Design and Development Project Scheduling with Uncertain Activity Durations

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Abstract

Aircraft design and development projects involve high levels of uncertainty due to their complex structure, making effective project scheduling critically important. This study addresses the limitations of deterministic scheduling approaches in managing uncertain activity durations within projects conducted in collaboration with Turkish Aerospace Industries. The main problem lies in the inability of traditional methods to adequately capture uncertainties arising from design changes, certification processes, and supply chain disruptions. To overcome this issue, an integrated methodology based on Critical Path Method (CPM), PERT, and Monte Carlo Simulation is proposed and implemented. Initially, CPM established a baseline schedule with an estimated completion time of 2955 days. To incorporate uncertainty, PERT and a 10,000-iteration Monte Carlo Simulation were executed. Results demonstrated that the deterministic CPM approach provided a highly optimistic estimate with a mere 1.26% probability of realization. In contrast, PERT calculated the expected duration as 3071 days, while the Monte Carlo simulation revealed a more realistic average completion time of 3143 days under worst-case scenario distributions. The findings suggest that incorporating stochastic uncertainty into project planning significantly improves decision-making and enhances the accuracy of schedule predictions. This study contributes to the literature by proposing and numerically validating an integrated framework for analyzing uncertainty in aircraft development projects, providing a foundation for more robust and risk-aware planning practices in the defense industry.

Keywords

Project Scheduling, Risk Analysis, CPM, PERT, Monte Carlo Simulation.

1. Introduction

Aircraft development projects are highly complex processes that involve many interrelated activities such as design, manufacturing, integration, and testing. In addition to these processes, aircraft must also go through strict certification procedures conducted by aviation authorities to ensure that safety and airworthiness requirements are satisfied. Since certification activities are closely integrated with the main project schedule, delays occurring during the development phase may directly affect certification processes and overall project completion time. Due to the nature of aviation projects, many uncertainties may arise throughout the project's lifecycle. Factors such as design changes, supplier delays, subcontractor performance, and weather conditions during flight tests may create variability in activity durations and lead to deviations from the planned schedule. These uncertainties make it difficult to estimate the project's completion time accurately when traditional deterministic planning approaches are used.

In conventional project scheduling methods, activity durations are generally assumed to be fixed values. However, this assumption may lead to overly optimistic project completion estimates since real-life project environments contain various sources of uncertainty. Therefore, it is important to analyze how uncertainties in activity durations influence the overall project schedule. Based on this motivation, the aim of this study is to evaluate the impact of activity duration uncertainties on the project completion time of an aircraft development project. For this purpose, Critical Path Method (CPM), Program Evaluation and Review Technique (PERT), and Monte Carlo simulation are utilized to identify critical activities, analyze the project schedule, and obtain more realistic estimations for the project's completion time. The study aims to demonstrate how incorporating uncertainty into project scheduling can support more effective planning and decision-making.

The first stage of the study involves conducting a literature review, in which the methods used and previous studies on aviation and other industry projects' estimation under uncertain activity durations are examined. Subsequently, the theoretical foundations of the CPM, PERT, and Monte Carlo simulation methods are presented in sequence. In the application phase, the analyses carried out using the integrated CPM, PERT, and Monte Carlo simulation framework are discussed alongside their comparative findings. Finally, the results of the study are evaluated, future recommendations are provided, and the paper is concluded.

2. Literature Review

This section includes studies conducted between 2020 and 2025 on project management, risk analysis, CPM, PERT, and Monte Carlo simulation.

Tümtürk and Tümtürk (2020) examined the effectiveness of the critical path method (CPM) in managing complex construction projects using an urban transformation project in İzmir. The study demonstrates step-by-step how to define project activities, create a work breakdown structure, and construct a deterministic network diagram by establishing predecessor-successor relationships between activities. Analyzing the role of activities on the critical path in determining the total project duration, this research emphasizes the importance of creating a robust 'Baseline Schedule' during the planning phase of projects.

In 2020, Sheibani investigated the scheduling of aircraft ground handling operations with uncertain durations using critical path analysis and Monte Carlo simulation to improve ground handling, equipment availability, and crew assignment during aircraft turnaround times. The focus was on accurately predicting aircraft turnaround times and allocating resources more efficiently to improve ground handling operations, which can be complicated by cargo loading/unloading events, adverse weather conditions, or equipment failures. A case study conducted on a long-range wide-body jet (Boeing 787) demonstrated that modeling activities using probability distributions instead of deterministic durations resulted in more realistic turnaround time predictions and optimized resource utilization compared to traditional methods.

The study "Monte Carlo Simulation Applications for Construction Project Management" (2020) by Manoj Kumar Sharma examines the effectiveness of Monte Carlo simulation in managing risks and uncertainties encountered in complex construction projects. Unlike traditional methods, the research treats risk management as a holistic technique encompassing identification, qualitative and quantitative assessment, response, and control processes. Methodologically, the study utilizes probability distributions and Monte Carlo simulation to model uncertainties in the project schedule; the role of professional software like @RISK in decision support mechanisms is highlighted. The analysis concludes that simulation techniques are a superior tool for identifying threats to the primary project objectives of time, cost, and quality, offering project managers a much more reliable, probability-based forecast than deterministic approaches.

Fadjar, Nirmalawati, and Hidayat (2022) investigated the effect of uncertainty in activity durations on the total project duration by comparing CPM and Monte Carlo simulation results. The study statistically demonstrated that deterministic calculations generally yield optimistic results; however, simulations using a PERT distribution showed that the 'mean' and 'median' values were closer to reality. This analysis, performed on a simple network diagram, shows that the simulation provides project managers with a reliable timeframe that includes a risk factor, rather than a single completion date.

The study "Leveraging Monte Carlo Simulation for Project Risk Management: A Study on Pre-Mitigation and Post-Mitigation Techniques in Risk Registers" (2025), prepared by Armijos De La Cruz and colleagues, examines the

strategic use of Monte Carlo simulation to manage uncertainties that cause projects to deviate from budget and schedule targets. The research emphasizes that traditional single-point (deterministic) estimations are insufficient to reflect the risks in complex projects, arguing that more realistic predictions can be generated through probability distributions. In the study, thousands of iterations were run on the project's time and cost variables; this process involved identifying and analyzing risks and interpreting the simulation outputs (probability density functions and cumulative distribution plots). The results of the study revealed that Monte Carlo simulation provides project managers with a numerical probability (confidence levels) of the project's completion on a specific date or within budget, enabling the establishment of more informed decision-making mechanisms and the proactive mitigation of risks.

In his 2025 study, “Enhanced Monte Carlo simulation for project risk analysis: integrating cost and schedule impacts with time-shifted risks and dependency modeling,” Marc Bara criticized the static nature of traditional Monte Carlo simulations in project risk management, proposing a model that integrates cost and project schedule uncertainties in the time dimension. The study states that risks are not independent of each other and that the occurrence of one risk changes both the timing and probability of subsequent events. Therefore, instead of making a single prediction at the end of the project, this developed method creates dynamic P90 cost and delay curves daily to identify critical periods where risk exposure is concentrated. Comparative analyses have shown that classical methods significantly underestimate cost and time reserves due to their disregard for chain risk effects.

In a study by Ichsan et al. (2025), an approach integrating Monte Carlo simulation and PERT techniques was presented to more accurately predict the completion time of the Jakarta Central Railway Station construction project. The study argued that classical deterministic scheduling methods (CPM) are insufficient in managing uncertainties, and used optimistic, pessimistic, and most probable duration estimates for activities. In this large-scale railway project, the cumulative impact of risks on the project schedule was analyzed through probabilistic distributions. The simulation results calculated the probability of the project being completed on the contract date, providing managers with more realistic completion dates at different confidence levels. This study demonstrates with concrete data how numerical modeling of risks in complex projects with uncertain activity durations improves project success and prediction accuracy.

The aerospace sector is a field where deterministic planning methods often prove insufficient due to high technology requirements and complex certification processes. A review of uncertainty management studies in the literature reveals that Hu et al. (2016) focused on improved sampling techniques to reduce the computational burden of the classical Monte Carlo method in design optimization processes. Similarly, to address uncertainties arising from data scarcity, Ahn et al. (2018) proposed a quantitative index method called the "R-model," which standardizes risks through a numerical framework. These studies demonstrate the necessity of simulation-based approaches in modeling uncertain parameters within aerospace projects. In this context, our study focuses on aircraft development processes at TAI, presenting an integrated framework of CPM, PERT, and Monte Carlo simulation to enhance methodological depth in the sector.

While most studies in the literature compare methodologies theoretically, this proposed study numerically demonstrates—through simulation—the optimism bias created by CPM and PERT methods under uncertainties inherent in aviation projects. This study presents an original approach focusing on aircraft design and development processes in order to fill sectoral gaps in the literature and provide methodological depth. A review of the literature shows that project scheduling and risk analysis studies are predominantly concentrated on construction, logistics, or the maintenance of existing systems, while studies addressing the project management of aircraft—characterized by high technology requirements and a high degree of unknown parameters—remain quite limited. Our project aims to contribute to the sector by modeling these processes, which are difficult to manage due to their cyclical and uncertain nature. In this context, unlike existing studies that focus on a single method, CPM, PERT, and Monte Carlo simulation techniques will be addressed within an integrated framework. Through this three-way comparative approach, the method that yields results closest to actual completion times in defense industry projects will be analyzed, and a strategic decision-support framework that calculates the most accurate margin of deviation for project managers will be presented.

3. Methods

3.1 Critical Path Method (CPM)

The critical path method was developed in 1957 by J. E. Kelly and M. R. Walker to calculate downtime for maintenance in chemical plants and to complete the project in the shortest possible time (Temiz and Dursun 2016).

According to the critical path method, it is assumed that the durations of the activities in the project are known and precisely determined because similar projects have been carried out before (Chwastyk and Pisz 2020). The aim of this method is to determine the critical path to be followed to reach the project endpoint within the given time and to investigate different options that may arise if the durations of the activities change (Abuhasel 2023). After the network diagram is created, the first step is to determine the activity durations. In the critical path method, the exact duration of each activity is determined using the experience of the project management team and data from similar projects carried out in the past. After determining the activity durations, the earliest start, earliest completion, latest completion, latest start times, and slack value of each activity are calculated. After calculating the slack value, critical activities and the critical path can be determined by looking at these values. Activities with a slack value of zero are determined as critical activities, and the order of these activities forms the critical path of the project. The critical path includes all critical activities of the project, and the sum of the durations of these activities naturally gives the project completion time (Çorumlu 2022).

3.2 Program Evaluation and Review Technique (PERT)

The PERT technique was first applied in 1957 by the U.S. Navy to complete the Polaris Project—the construction of missile-launching submarines—two years ahead of schedule. As an event-oriented system, PERT offers numerous advantages for non-repetitive project types, R&D, prototype production, space exploration, and defense projects (Roy 2005). In cases where the duration of each activity in the project can be precisely determined, representing a deterministic method, the CPM method is utilized. Conversely, the PERT method is based on the expected durations of activities, thus constituting a stochastic model (Milojević et al. 2022).

Creating a PERT network requires comprehensive information about key project activities or tasks. Accurately matching preceding and subsequent activities for each task is critical. The completion time for an activity can be obtained through an analysis that typically includes the shortest, longest, and most likely durations (Yudistira 2024). In this method, durations follow a beta distribution, and the critical path of the project is determined by making three estimates for each activity. PERT development is based on six steps, as follows (Sachs and Gabriel 2022; Ljiljanić et al. 2022):

1. Defining the project and identifying all key activities or tasks
2. Establishing the connections between these activities; determining which should come before or after the others (priority relationship)
3. Defining the network connecting all activities
4. Assigning estimated duration and cost to each activity
5. Calculating the critical path, i.e., the longest time path within the network
6. Using the network in project planning, scheduling, and control processes

One of the aims of using the PERT technique is to determine how much time is needed to complete the project. Therefore, PERT directly affects the success of the project by identifying; It uses time as a common denominator to directly analyze time, cost, and performance. Using the PERT technique, the earliest time of an event or the start or completion times of an activity can be determined (Kızıl 2020).

Managers may have access to information regarding time estimates from foremen, suppliers, subcontractors, and other service providers. This information also enables managers to determine the central measure and the measure of dispersion (standard deviation) for a project's completion time (Bagshaw 2021).

Many simplifying assumptions are considered in the PERT method; therefore, studies also exist under the assumption that the probability distributions of activity durations differ from the beta distribution (Çorumlu 2022). The project completion time is assumed to follow a normal distribution (Desticioğlu Taşdemir 2022). When there is more than one critical path in the project, the path with the largest variance is determined as the critical path.

3.3 Monte Carlo Simulation

Monte Carlo simulation is a method that encompasses a statistical sampling technique to generate approximate solutions to numerical problems. In this method, a model of a real-life system or situation is developed, and this model includes specific variables. These variables have different possible values represented by probability distributions defined for each variable. Monte Carlo simulation simulates the entire system hundreds or thousands of times, selecting a number for each variable each time according to the probability distribution of that variable. The output is

the probability distribution of the overall value for the entire system calculated over the iterations (Kwak and Ingall 2009).

Monte Carlo simulation shows a strong correction effect in estimating project duration, reducing the error in the estimation value of the traditional PERT method to a certain extent (Chen et al. 2009). The primary benefit of using the Monte Carlo method in projects is that this technique is quite powerful in quantifying and understanding the effects of uncertainties in projects. Ignoring uncertainties leads to deviations from targets in both the project schedule and budget. According to Williams (2003), cited by Kwak and Ingall (2009), although there are many approaches to project scheduling, the main problem with these analytical approaches stems from their inability to be used in practical situations due to their restrictive assumptions. These analytical methods can only provide specific moments related to project durations, instead of the distribution of project durations, which is useful in determining the confidence level regarding project completion time. In particular, the standard PERT method ignores path connections in the calculation of project networks. This causes the project duration to appear shorter than it is. The Monte Carlo method, on the other hand, evaluates such situations with hundreds or thousands of cycles (Kwak and Ingall 2009). The Monte Carlo method relies on the shape of the distribution to achieve greater accuracy. Additionally, the Monte Carlo approach offers flexibility in using various distributions such as beta, normal, triangular, and uniform for activity durations (Van Slyke 1963).

4. Application

Figure 1 below shows the flowchart of the project. This flowchart provides a visual summary of how the work will proceed.

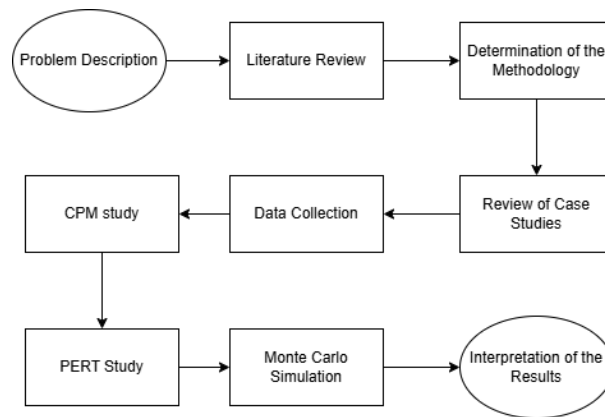


Figure 1. Flow Chart

The data used in the project was obtained from Turkish Aerospace Industries Inc. (TAI). The activities used in the project, their durations, and their dependencies were prepared using past experiences and general aviation and aircraft structure knowledge. The study includes the following main headings: Program Milestones, Program Deliverables, Integrated Program Management, Systems Engineering and Integration, Software/Hardware, Air Vehicle Systems, Airframe, Flight Control Systems, Avionics and Mission System, Propulsion Integration and Certification Activities. Lower-level activities are located under these main headings.

4.1 Critical Path Method (CPM)

This section presents an application to examine the impact of uncertainties arising in operational timelines of aircraft development projects on project completion time. The application involved creating a project network and performing

analysis using the CPM method. Subsequent stages will involve analysis using the PERT method, and Monte Carlo simulation will be used to more realistically assess the impact of uncertainties on project duration (Figure 2).

Task Mode	Task Name	Predecessors	Successors	Start	Finish	Duration	Free Slack	Total Slack
	2nd Air Vehicle's Aircraft Systems Test	51	59	Tue 4.11.25	Wed 3.12.25	30 days	0 days	0 days
	• Test and Evaluation Phase			Wed 6.08.25	Thu 29.10.26	450 days	95 days	95 days
	• Ground Test			Wed 6.08.25	Sat 2.05.26	270 days	0 days	0 days
	• 1st Prototype Aircraft			Wed 6.08.25	Fri 2.01.26	150 days	120 days	120 days
	Ground Test	138;50FF	209;57	Wed 6.08.25	Mon 3.11.25	90 days	0 days	120 days
	Ground Vibration Test	56	209;62	Tue 4.11.25	Fri 2.01.26	60 days	0 days	120 days
	• 2nd Prototype Aircraft			Thu 4.12.25	Sat 2.05.26	150 days	0 days	0 days
	Ground Test	138;52	209;60	Thu 4.12.25	Tue 3.03.26	90 days	0 days	0 days
	Ground Vibration Test	59	209;63	Wed 4.03.26	Sat 2.05.26	60 days	0 days	0 days

Figure 2. Identification of critical activities using MS Project

A total of 214 activities were examined in the project. The CPM analysis revealed that 70 activities were critical. Based on this analysis, the project duration was found to be 2955 days, with an anticipated completion date of February 2, 2028. The production, integration management, requirements management, aircraft manufacturing and assembly phases (1st and 2nd aircraft), software/hardware phase, and certification phases (Phase 3 and Phase 4) were identified as being on the critical path.

As shown in Figure 3, when the free and total slack of the Ground Test and Ground Vibration Test were calculated, it was found that the total slack, and therefore the free slack, was 0. Because the total slack of these two activities is 0, delays in these activities cause delays in the total project duration. Therefore, ground test and ground vibration test are critical activities.

Task Mode	Task Name	Predecessors	Successors	Start	Finish	Duration	Free Slack	Total Slack
70	Program Management Plan	88FF	4	Tue 31.03.20	Tue 31.03.20	1 day	1 day	166 days
71	Program Risk Management Plan	92FF	4	Fri 31.01.20	Fri 31.01.20	1 day	61 days	226 days
72	Program Acquisition Plan	96FF	4	Fri 31.01.20	Fri 31.01.20	1 day	61 days	226 days
73	Systems Engineering Management Plan	101	4	Wed 1.04.20	Wed 1.04.20	1 day	0 days	165 days

Figure 3. Slack evaluation of systems engineering activities in MS Project

Looking at the System Engineering Management Plan activity, as illustrated in Figure 4, the total slack is found to be 165 days. This indicates that a delay of 165 days in this activity would not cause a delay in the project completion time. However, when looking at the free slack of the activity, it is seen to be 0. This shows that a delay in the System Engineering Management Plan activity would also cause a delay in the subsequent Project Management Review activity.

Task Mode	Task Name	Predecessors	Successors	Start	Finish	Duration	Free Slack	Total Slack
70	Program Management Plan	88FF	4	Tue 31.03.20	Tue 31.03.20	1 day	1 day	166 days
71	Program Risk Management Plan	92FF	4	Fri 31.01.20	Fri 31.01.20	1 day	61 days	226 days
72	Program Acquisition Plan	96FF	4	Fri 31.01.20	Fri 31.01.20	1 day	61 days	226 days
73	Systems Engineering Management Plan	101	4	Wed 1.04.20	Wed 1.04.20	1 day	0 days	165 days
74	Software/Hardware Management Plan	153	6	Wed 8.09.21	Wed 8.09.21	1 day	30 days	30 days
75	Technology Management and Integration Plan	101	5	Mon 28.09.20	Mon 28.09.20	1 day	0 days	0 days
76	Air Vehicle Requirements Document	106	6	Fri 25.06.21	Fri 25.06.21	1 day	105 days	105 days
77	Air Vehicle Design Description	120	7	Fri 22.07.22	Fri 22.07.22	1 day	0 days	0 days
78	Configuration Management Plan	102	4	Wed 1.04.20	Wed 1.04.20	1 day	0 days	165 days
79	Safety Program Plan	123	4	Wed 1.04.20	Wed 1.04.20	1 day	0 days	165 days
80	Environmental Program Plan	132	6	Mon 12.04.21	Mon 12.04.21	1 day	179 days	179 days

Figure 4. Schedule flexibility analysis for non-critical activities

As shown in Figure 4, looking at the Program Risk Management Plan activity, the total slack value is 226 days, and the free slack value is 61 days. A delay of up to 226 days in this activity does not affect the total project completion time. However, a delay exceeding 61 days (e.g., 62 days) will cause a delay in the early start of the subsequent activity. For example, since the Environmental Program Plan activity has both a free and total slack of 179 days, a delay exceeding 179 days will cause delays in both the early start of the subsequent activities and the total project completion time.

4.2 Program Evaluation and Review Technique (PERT)

Unlike CPM, instead of using a single deterministic duration, this method calculates the expected time using the coefficients a (1), m (4), and b (1) to increase the confidence level. Based on the data obtained from the company and these coefficients, a Python script was developed and executed to generate the project schedule. The expected completion time was found to be 3071 days, with a variance of 2960.8887. As a result of the study, the total number of critical activities, which was identified as 70 in the CPM analysis, was determined to be 45 in the PERT analysis.

Table 1. PERT Results Table

Activity	Predecessors	Successors	Optimistic Duration	Most Likely Duration	Pessimistic Duration	Expected Duration	Total Slack	Start Date	Finish Date
2nd Air Vehicle's Aircraft Systems Test	51	59	30	30	61	35,16666667	0	31.12.2025	4.02.2026
Test and Evaluation Phase			450	450	495	475	0	28.09.2025	16.01.2027
Ground Test			270	270	297	288	0	28.09.2025	13.07.2026
1st Prototype Aircraft			150	150	165	162	0	28.09.2025	10.03.2026
Ground Test	138,50FF	209,57	90	90	121	95,16666667	125,83	28.09.2025	1.01.2026
Ground Vibration Test	56	209,62	60	60	105	67,5	125,83	1.01.2026	10.03.2026
2nd Prototype Aircraft			150	150	165	159	0	4.02.2026	13.07.2026
Ground Test	138,52	209,6	90	90	121	95,16666667	0	4.02.2026	11.05.2026
Ground Vibration Test	59	209,63	60	60	83	63,83333333	0	11.05.2026	13.07.2026

In the CPM analysis, the total slack value for the Ground Test and Ground Vibration Test activities was found to be 120 days, whereas this value shifted to 125.83 days in the PERT analysis, as illustrated in Table 1. These two activities do not lie on the critical path. The reason for this variance is that while CPM is deterministic, PERT is stochastic and incorporates pessimistic durations, thereby extending the critical path of the project.

Table 2. PERT Results Table

Activity	Predecessors	Successors	Optimistic Duration	Most Likely Duration	Pessimistic Duration	Expected Duration	Total Slack	Start Date	Finish Date
Systems Engineering Management Plan	101	4	1	1	2	1,166666667	191,5	2.04.2020	3.04.2020
Software/Hardware Management Plan	153	6	1	1	2	1,166666667	30,5	12.10.2021	13.10.2021
Technology Management and Integration Plan	103	5	1	1	2	1,166666667	23,83	2.10.2020	3.10.2020
Air Vehicle Requirements Document	106	6	1	1	2	1,166666667	110,5	24.07.2021	25.07.2021
Air Vehicle Design Description	120	7	1	1	2	1,166666667	5,5	29.08.2022	31.08.2022
Configuration Management Plan	102	4	1	1	2	1,166666667	191,5	2.04.2020	3.04.2020
Safety Program Plan	123	4	1	1	2	1,166666667	191,5	2.04.2020	3.04.2020

In the CPM analysis, the total slack values for the Technology Management and Integration Plan and Airvehicle Design Description activities were found to be 0, whereas in the PERT analysis, these values changed to 23.83 and 5.5, respectively (Table 2). Consequently, these activities ceased to be critical activities in the PERT analysis.

In the CPM analysis, the expected completion time of the project was determined to be 2955 days. As shown below, when this scenario was evaluated using the normal distribution approach of PERT, referencing the calculated Z-value in the standard normal table revealed that the probability of completing the project within 2955 days is 1.26%.

$$Z = \frac{X - \mu}{\sigma} \quad Z = \frac{2955 - 3071}{\sqrt{2960,8887}} = -2,2362 \sim -2,24$$

4.3 Monte Carlo Simulation

In this section, based on an evaluation of the activities obtained from the company at the work package level, four different distribution models (normal, uniform, triangular, and lognormal) were utilized to represent the uncertainty in activity durations and risk impacts, depending on data availability and the level of information detail. Using these four specified distributions, a Python script was developed for the Monte Carlo Simulation, and 20 runs of 10,000 iterations each were executed. Additionally, the criticality index of each activity was calculated, and the generated graphs were interpreted. As stated by Hajdu (2013), activity duration distributions and their parameters in project networks can be flexibly defined at any desired level of the Work Breakdown Structure (WBS). This structure allows for the selection of different distribution models directly on a work package basis, and the determined distribution can

also be applied to sub-tasks. The triangular distribution is applied by defining three parameters—optimistic (O), most likely (M), and pessimistic (P) durations—only in cases where expert estimates are available. This distribution is suitable for situations with limited empirical data, which are frequently encountered in aerospace projects (Avief et al. 2026). In the project schedule, the Triangular Distribution was utilized for activities that have differing optimistic, most likely, and pessimistic duration estimates, and for which limited information is available. The lognormal distribution is a continuous and asymmetrical distribution frequently used to model activity or task durations. It is predominantly used for non-standard, complex tasks where employees are inexperienced. Especially when things go wrong, time overruns typically occur in these tasks (Visser 2016). In the project schedule, the Lognormal Distribution was used specifically for activities where the company lacks experience and where any prolongation would directly impact the overall project completion time. Hajdu and Bokor (2014) state that the uniform distribution is based on the optimistic (a) and pessimistic (b) extreme values when modeling activity durations. Accordingly, for certain activities in the project schedule where historical data is limited, the optimistic, most likely, and pessimistic duration estimates were considered equal ($a = m = b$) in terms of likelihood. In these cases, the Uniform Distribution was preferred under the assumption that every duration within the estimated range has an equal probability of occurrence. The Normal Distribution is one of the most frequently utilized models for representing statistical uncertainty in project management due to its symmetrical structure and its ability to represent central tendency data. It is particularly ideal for scenarios where historical data is abundant, activity durations cluster around an average value rather than extreme values, and the central limit theorem is applicable (Shtub et al. 2005). In the project schedule, the Normal Distribution was chosen for activities where the company is highly experienced.

Using the parameters of the four aforementioned distributions, 20 runs of 10,000 iterations each were executed. The optimistic, average, and pessimistic duration estimates for these 20 runs are presented in Table 3.

Table 3. Duration Estimates for 20 Runs

Runs	Optimistic	Most Likely	Pessimistic
1	3024	3142	3315
2	3031	3142	3327
3	3017	3142	3323
4	3022	3141	3325
5	3028	3142	3312
6	3020	3142	3326
7	3020	3142	3310
8	3030	3142	3316
9	3021	3142	3315
10	3036	3142	3365
11	3035	3142	3316
12	3022	3143	3305
13	3038	3141	3332
14	3026	3141	3313
15	3033	3141	3298
16	3027	3142	3332
17	3038	3141	3333
18	3038	3142	3320
19	3026	3141	3311
20	3039	3142	3343

Based on the results of the 20 runs as shown in Table 3, the project completion times were found to be within the following ranges:

- The most optimistic project completion: 3017 – 3039 days,
- The average project completion: 3141 – 3143 days,
- The most pessimistic project completion: 3298 – 3365 days.

The Criticality Index (CI) is defined as the proportion of simulation runs in which activities appear on the critical path (Osgood 2004). Among the 20 runs, for the worst-case scenario having an average duration of 3143 days, the criticality index for each activity was determined as follows:

$$CI = \left(\frac{\text{Number of runs in which activities appear on the critical path}}{\text{Total number of runs}} \right) * 100$$

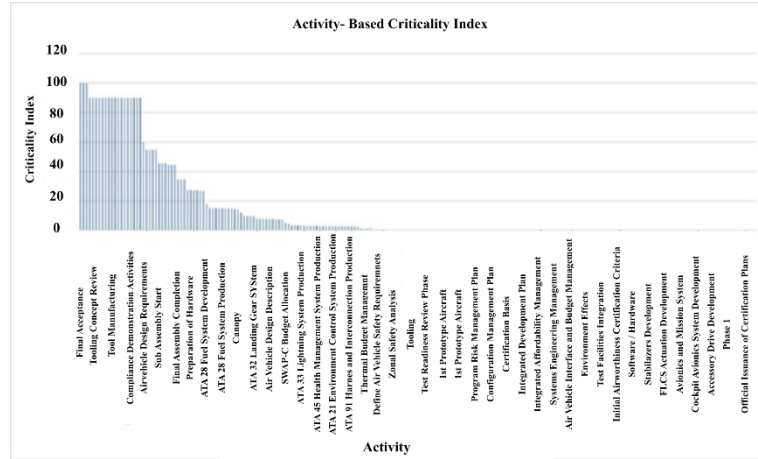


Figure 5. Activity-Based Criticality Index Histogram

According to the histogram as illustrated in Figure 5, the criticality index of the Final Acceptance and Project Completion (Except Certification) activities was found to be 100% across the 10,000 iterations. The criticality index for the Detail Tooling Complete, Subassembly Tooling Complete, and 15 associated activities was determined to be 90.01%. Conversely, the Ground Test, 1st Prototype Aircraft, and 111 accompanying activities were found to have a criticality index of 0. Based on these findings, it was determined that the Final Acceptance and Project Completion activities lie on the critical path, whereas the 113 activities with a criticality index of 0 do not.

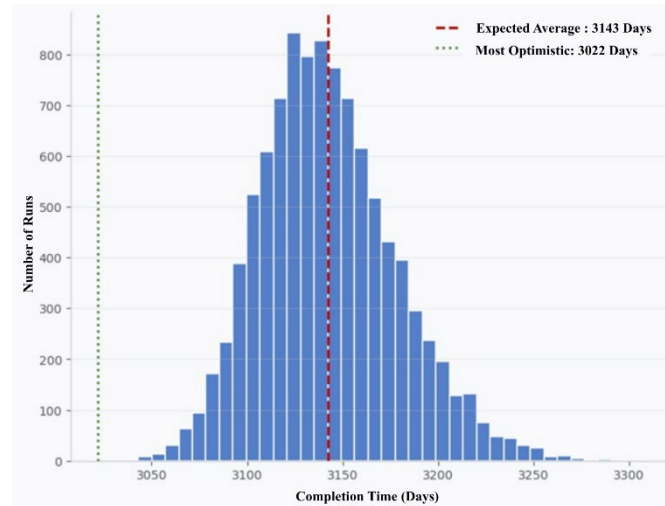


Figure 6. Project Completion Time Distribution

Figure 6 presents the histogram of the estimates generated over 10,000 iterations for the worst-case scenario. Across these 10,000 iterations, the expected average project completion time is 3143 days.

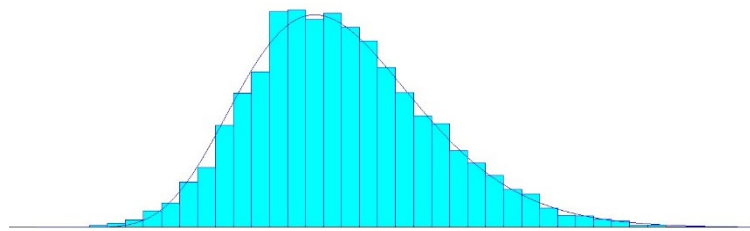


Figure 7. Input Analyzer View of the Distribution Curve

Function	Sq Error
Erlang	0.000222
Gamma	0.00026
Beta	0.000971
Lognormal	0.00104
Normal	0.00123
Weibull	0.0022
Triangular	0.0107
Uniform	0.0326
Exponential	0.0417

Figure 8. Square Errors for Each Distribution

Using the Arena Input Analyzer on the project data, the square errors for each distribution were obtained, as presented in Figure 8. A comparison of these results indicates that the best fit belongs to the Erlang distribution (Figure 7). However, since the p-value for the Erlang distribution is less than 0.005 ($p < 0.005$), the hypothesis that the curve fits this distribution could not be validated. Therefore, it can be concluded that the distribution curve exhibits a slightly right-skewed structure. Scenarios indicating the probability of the project taking significantly longer than expected (between 3250 and 3300 days) are spread over a broader range compared to the probabilities of early completion. An analysis of the frequency densities reveals that while the project is most likely to be completed between 3120 and 3150 days, the potential for a delayed completion is greater than the potential for an early completion.

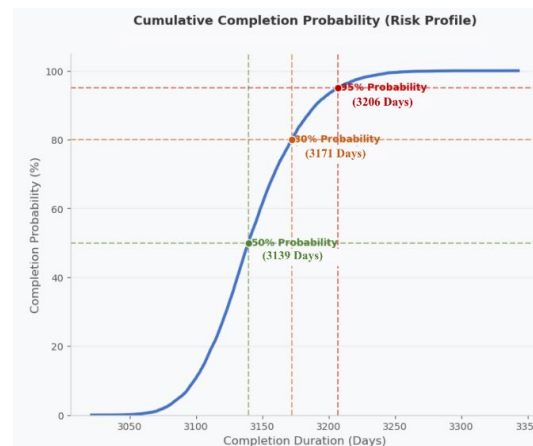


Figure 9. Cumulative Completion Probability (Risk Profile)

The graph presented in Figure 9 illustrates the cumulative completion probabilities of the project. Based on the data obtained from 10,000 iterations, the probability of completing the project within 3139 days is 50%, within 3171 days is 80%, and within 3206 days is 95%. Rather than relying on deterministic estimates, this risk profile enables the project manager to make informed decisions by evaluating the cost/time trade-off. In a scenario with exceedingly high delay penalties, the target should be set at 3206 days, whereas a duration of 3171 days could be targeted under a more flexible contract. Furthermore, when the expected project completion time derived from the traditional PERT analysis (3071 days) is evaluated against the Monte Carlo cumulative probability graph in Figure 9, it is observed that the probability of project completion within this timeframe is less than 5%. It was determined that the PERT method yields an overly optimistic duration estimate due to its deterministic nature. In contrast, by accounting for all project uncertainties and right-skewed risk distributions, the Monte Carlo simulation generates a much more realistic and

reliable timeframe, such as 3139 days for a 50% probability. This finding demonstrates the necessity of utilizing simulation-based probabilistic approaches rather than single-point PERT estimates in risky and complex projects.

5. Conclusion

In this study, the scheduling process of an aircraft design and development project, conducted in collaboration with Turkish Aerospace Industries (TUSAŞ), was comparatively analyzed using the CPM, PERT, and Monte Carlo simulation methods. While the CPM analysis predicted a project completion time of 2955 days, the PERT method calculated this duration as 3071 days. However, the Monte Carlo simulation revealed that, under the worst-case scenario, the project would be completed in an average of 3143 days. It was determined that the probability of completing the project within the 2955-day timeframe predicted by CPM is a mere 1.26%. Similarly, even the probability of achieving the PERT estimate (3071 days) was found to remain below 5% within the Monte Carlo risk profile. Rather than merely identifying a single "critical path," the simulation outputs numerically demonstrated which activities carry a higher risk of causing project delays through the Criticality Index. Specifically, the "Final Acceptance" and "Project Completion" activities were verified as critical across all scenarios.

As a limitation, this study focused exclusively on the time dimension; future research could integrate "Cost and Schedule Risk Analysis" models to evaluate the budgetary impacts of activity delays. Furthermore, incorporating resource constraints (e.g., manpower, equipment) and real-world factors like weekends and specific working hours into the Python scripts would yield even more realistic simulations.

By replacing the deterministic limitations of traditional CPM with a stochastic approach utilizing various statistical distributions, the 10,000-iteration Monte Carlo simulation provides decision-makers with an innovative early warning and strategic planning infrastructure. This proactive model actively supports economic and operational sustainability in high-budget aerospace and defense projects. Accurate planning of concurrent tasks minimizes process wastes—such as rework or faulty prototype production—and prevents potential cost overruns. Consequently, it ensures the efficient use of resources and the long-term predictability of corporate processes.

Ultimately, this research serves as a concrete example of university-industry collaboration by effectively managing schedule uncertainties in complex aircraft development projects. Integrating such academic models into the defense industry not only enhances the likelihood of timely project delivery but also directly drives sectoral innovation.

References

- Abuhasel, K., Sustainable green city development project analysis using the critical path method (CPM) and the crashing project method on time and cost optimization, *Engineering, Technology & Applied Science Research*, vol. 13, no. 3, pp. 10973–10977, 2023.
- Ahn, H., Kim, H. and Choi, H.-L., Integrated risk management method development for multiple aerospace projects using a single index expression, *International Journal of Aeronautical and Space Sciences*, vol. 19, pp. 1052–1062, 2018.
- Armijos De La Cruz, B. A., Castro Esparza, J. R., Leoro Benitez, J. F. and Armijos De La Cruz, W. Y., Leveraging Monte Carlo simulation for project risk management: A study on pre-mitigation and post mitigation techniques in risk registers, *Ciencia Latina Revista Científica Multidisciplinar*, vol. 9, no. 5, 2025.
- Avief, R. M. S., Hidayat, S. and Jimmy, A risk-integrated CPM–PERT and Monte Carlo simulation approach for aircraft overhaul scheduling: Empirical evidence from military maintenance systems, *Journal Européen des Systèmes Automatisés*, vol. 59, no. 3, pp. 641–649, 2026.
- Bagshaw, K. B., New PERT and CPM in project management with practical examples, *American Journal of Operations Research*, vol. 11, no. 4, pp. 215–226, 2021.
- Bara, M., Enhanced Monte Carlo simulation for project risk analysis: Integrating cost and schedule impacts with time shifted risks and dependency modeling, *Applied Operations and Analytics*, vol. 1, no. 1, pp. 1–15, 2025.
- Chen, Q.-W., Li, G.-Y. and Zhuang, Q.-H., The analysis of project schedule uncertainty: Based on Monte Carlo simulation, *Proceedings of the International Conference on Management and Service Science*, pp. 1–4, 2009.
- Chwastyk, A. and Pisz, I., Critical path analysis with imprecise activities times, *Sustainable Economic Development and Application of Innovation Management*, pp. 2004–2013, 2020.
- Çorumlu, V., Proje çizelgeleme problemlerinde bulanık doğrusal programlama ile proje tamamlanma süresinin belirlenmesi ve bir yazılım projesinde uygulanması, M.Sc. Thesis, Başkent Üniversitesi, 2022.

- Desticioğlu Taşdemir, B., Project planning with CPM and PERT methods: Example of defence industry, *Journal of Naval Sciences and Engineering*, vol. 18, no. 2, pp. 363–385, 2022.
- Fadjar, A., Nirmalawati and Hidayat, N., Estimating project completion time with Monte Carlo simulation, *Rekonstruksi Tadulako: Civil Engineering Journal on Research and Development*, vol. 3, no. 2, pp. 21–26, 2022.
- Hajdu, M., Effects of the application of activity calendars on the distribution of project duration in PERT networks, *Automation in Construction*, vol. 35, pp. 397–405, 2013.
- Hajdu, M. and Bokor, O., The effects of different activity distributions on project duration in PERT networks, *Procedia - Social and Behavioral Sciences*, vol. 119, pp. 766–775, 2014.
- Hu, X., Chen, X., Parks, G. T. and Yao, W., Review of improved Monte Carlo methods in uncertainty-based design optimization for aerospace vehicles, *Progress in Aerospace Sciences*, vol. 86, pp. 20–27, 2016.
- Ichsan, M., Isvara, W. and Karim, S., Monte Carlo simulation for enhancing the schedule completion forecast of Jakarta Central Railway Station construction project, *Applied Sciences*, vol. 15, no. 13, pp. 7464, 2025.
- Kızıl, F., İnsansız hava aracı (İHA) yapısının proje değerlendirme ve gözden geçirme tekniği (PERT) ile planlanması, M.Sc. Thesis, Anadolu Üniversitesi, 2020.
- Kwak, Y. H. and Ingall, L., Exploring Monte Carlo simulation applications for project management, *IEEE Engineering Management Review*, vol. 37, no. 2, pp. 83–91, 2009.
- Ljiljanić, N., Rajić, Z. and Paunović, T., Use of PERT (Program Evaluation and Review Technique) and PDM (Precedence Diagramming Method) in organizing modern vegetable seedling production, *Economics of Agriculture*, vol. 69, no. 1, pp. 119–135, 2022.
- Milojević, I., Krstić, D. and Jovičić, A., Application of the PERT method in the audit of business of agricultural enterprises, *Economics of Agriculture*, vol. 69, no. 4, pp. 1125–1137, 2022.
- Osgood, N., Probabilistic planning 2 [Ders notları], Massachusetts Institute of Technology, OpenCourseWare, 2004. https://ocw.mit.edu/courses/1-040-project-management-spring-2004/5df134b4fd6bb66f732d9a413dd3da6e_112prob_plan2_04.pdf
- Roy, R. N., *A modern approach to operations management*, New Age International Publishers, 2005.
- Sachs, M. C. and Gabriel, E. E., Event history regression with pseudo-observations: Computational approaches and an implementation in R, *Journal of Statistical Software*, vol. 102, no. 9, pp. 1–34, 2022.
- Sharma, M. K., Monte Carlo simulation applications for construction project management, *International Journal of Civil Engineering and Technology*, vol. 11, no. 2, pp. 88–100, 2020.
- Sheibani, K., Scheduling aircraft ground handling operations under uncertainty using critical path analysis and Monte Carlo simulation: Survey and research directions, *International Journal of Business Strategy and Automation*, vol. 1, no. 1, pp. 37–45, 2020.
- Shtub, A., Bard, J. F. and Globerson, S., *Project management: Processes, methodologies, and economics*, Pearson Prentice Hall, 2005.
- Temiz, N. and Dursun, E., PERT tekniğinin liman deniz hizmetleri otomasyonu projesine uygulanması, *Dokuz Eylül Üniversitesi Denizcilik Fakültesi Dergisi*, vol. 8, no. 1, pp. 1–29, 2016.
- Tümtürk, A. and Tümtürk, E., Kritik yol metodu ile kentsel dönüşüm bina projelerinin programlanması: İzmir Karşıyaka örneği, *Dumlupınar Üniversitesi Sosyal Bilimler Dergisi*, no. 63, pp. 175–190, 2020.
- Van Slyke, R. M., Monte Carlo methods and the PERT problem, *Operations Research*, vol. 11, no. 5, pp. 839–860, 1963.
- Visser, J. K., Suitability of different probability distributions for performing schedule risk simulations in Project management, *Proceedings of PICMET '16: Technology Management for Social Innovation*, pp. 1030–1037, 2016.
- Yudistira, I. G. A. A., Nariswari, R., Arifin, S., Abdillah, A. A., Prasetyo, P. W. and Susyanto, N., Program evaluation and review technique (PERT) analysis to predict completion time and project risk using discrete event system simulation method, *CommIT Journal*, vol. 18, no. 1, pp. 67–76, 2024.

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