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Original Article

An Integrated Critical Path Method and PERT Approach for Schedule Performance Evaluation of Drainage Construction Projects

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Abstract

Time control is a critical factor in the successful delivery of drainage construction projects, which are often characterized by high complexity, limited working space, and significant uncertainty in activity durations. Delays in such projects can have substantial economic and social impacts, underscoring the need for reliable schedule performance evaluation. This study aims to evaluate the schedule performance of a drainage construction project by integrating the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT) using a Work Breakdown Structure (WBS)-based approach. The research employs secondary data in the form of a project schedule presented as a weekly S-curve with a planned duration of 180 calendar days. A CPM network is developed at the WBS level to identify the dominant project path, followed by applying PERT to critical activities to assess duration uncertainty and completion probability. The results indicate that the dominant path consists of preparation works, earthworks and piling works, drainage channel construction, and pedestrian access works, with drainage channel construction identified as the most critical activity. The PERT analysis reveals that uncertainty in dominant activities increases the expected project duration and reduces the likelihood of on-time completion. These findings suggest that deterministic scheduling alone may underestimate project timelines, whereas integrating CPM and PERT provides a more realistic evaluation framework. The study concludes that a WBS-based CPM–PERT approach is effective for assessing schedule performance under data limitations and offers practical insights for improving project time control and decision-making.

1. Introduction

Time management is a fundamental determinant of success in construction project delivery, particularly in infrastructure projects such as urban drainage systems, which are inherently complex and highly sensitive to delays. Effective scheduling ensures that project activities are coordinated efficiently, resources are optimally allocated, and project objectives are achieved within the planned timeframe and budget. However, in practice, many construction projects experience delays due to uncertainties in activity durations, limited working space, environmental constraints, and coordination challenges among stakeholders (Maravas & Pantouvakis, 2012; Derbe et al., 2020).

Urban drainage construction projects play a critical role in mitigating flooding risks and improving environmental quality, especially in rapidly urbanizing regions. These projects typically involve multiple interdependent activities, including preparation works, earthworks, structural construction, and finishing works, all of which must be carefully sequenced and monitored. The dynamic nature of construction environments, such as weather variability, soil conditions, and interference with existing infrastructure, introduces significant uncertainty into project schedules, making time control a challenging task (Hajdu & Bokor, 2014; Fauzah et al., 2024).

To address scheduling challenges, various project management techniques have been developed, among which the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT) are the most widely used. CPM, introduced by Kelley and Walker

(1959), is a deterministic scheduling tool that identifies the sequence of activities known as the critical path that directly determines the total project duration. By focusing on activities with zero float, CPM enables project managers to prioritize monitoring and control efforts on tasks that have the greatest impact on project completion (Kelley & Walker, 1959; Bagshaw, 2021). This method has been widely applied in construction projects due to its ability to provide a clear structure for activity dependencies and to facilitate decision-making related to resource allocation and schedule optimization (Suryono & Hasbullah, 2020).

Despite its advantages, CPM has limitations in handling uncertainty because it assumes that activity durations are fixed and known with certainty. In real-world construction projects, such assumptions are rarely valid, as activity durations are often influenced by unpredictable factors such as weather conditions, labor productivity, material availability, and site-specific constraints. To overcome this limitation, PERT was developed as a probabilistic scheduling technique that accounts for uncertainty by using three-point estimates: optimistic, most likely, and pessimistic durations (Malcolm et al., 1959; Trietsch & Baker, 2012). This approach allows project managers to estimate expected activity durations and assess the probability of completing a project within a specified timeframe.

The integration of CPM and PERT has been recognized as a powerful approach for improving project scheduling accuracy and reliability. While CPM provides a deterministic framework for identifying critical activities, PERT complements it by quantifying uncertainty and evaluating schedule risk. Previous studies have demonstrated that combining these methods enhances decision-making by offering both structural clarity and probabilistic insight into project timelines (Ba'Its et al., 2020; Ridwan, 2025). Furthermore, the integration enables project managers to develop more realistic schedules, anticipate potential delays, and implement proactive mitigation strategies (Itani, 2023).

Recent advancements in project scheduling research have also explored the use of optimization techniques and computational models to improve CPM–PERT performance. For example, genetic algorithms have been applied to optimize scheduling in complex networks, enabling faster and more accurate identification of critical paths and project durations (Calp & Akcayol, 2018). Additionally, the incorporation of linear programming techniques has been shown to effectively balance time and cost trade-offs, further enhancing project efficiency (Agyei, 2015; Mansur Nuhu et al., 2024). These developments highlight the growing importance of integrating traditional scheduling methods with modern analytical tools.

Moreover, empirical studies in construction projects consistently emphasize the importance of focusing on critical-path activities to prevent delays. Applications of CPM and PERT across case studies, including housing construction, infrastructure development, and industrial maintenance projects, have demonstrated significant improvements in project completion time, cost efficiency, and risk management (Sukamta et al., 2026; Hanifa et al., 2024; Andiyan et al., 2021). These findings reinforce the relevance of CPM–PERT integration in addressing practical challenges in construction project management.

However, a key limitation in many real-world projects, particularly in developing countries, is the lack of detailed activity-level data required for conventional CPM and PERT analysis. Project schedules are often available only in aggregated forms, such as Work Breakdown Structure (WBS)-based schedules or S-curves, which do not explicitly define activity dependencies. This limitation necessitates the development of alternative approaches that can adapt CPM–PERT techniques to data-constrained environments while still providing meaningful insights for project control (Maravas & Pantouvakis, 2012).

In addition, emerging technologies such as Building Information Modeling (BIM) and augmented reality (AR) have been introduced to enhance project scheduling and monitoring by improving real-time communication and visualization on construction sites (Wang et al., 2014). These technologies offer new opportunities for integrating scheduling methods with digital tools, thereby increasing the effectiveness of project control and reducing the likelihood of errors and delays.

Given these challenges and developments, this study aims to evaluate the schedule performance of a drainage construction project by integrating CPM and PERT using aggregated schedule data based on the Work Breakdown Structure. The study seeks to identify the dominant project path, analyze uncertainty in critical activities, and assess the probability of completing the project within the planned duration. By adopting a WBS-based CPM–PERT approach, this research contributes to the existing literature by providing a practical, adaptable framework for project schedule evaluation under limited data availability.

Ultimately, this study is expected to offer both theoretical and practical contributions. Theoretically, it extends the application of CPM–PERT integration to aggregated scheduling contexts. In practice, it provides project managers with a structured approach to improve time management, enhance decision-making, and mitigate schedule risks in drainage construction projects and similar infrastructure developments.

2. Literature Review

2.1. Theoretical Foundation of Project Scheduling (CPM and PERT)

Project scheduling is a central component of construction project management, as it determines the sequence, duration, and interdependence of activities required to achieve project objectives. Among the most widely used techniques are the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT). The CPM, introduced by Kelley and Walker, provides a deterministic framework for identifying the sequence of activities that directly influence project completion time. It focuses on critical activities with zero float, enabling project managers to prioritize monitoring and control efforts (Kelley & Walker, 1959).

In contrast, PERT was developed to address uncertainty in project scheduling by incorporating probabilistic time estimates (optimistic, most likely, and pessimistic). Early applications of PERT demonstrated its effectiveness in handling research and development projects characterized by high uncertainty (Malcolm et al., 1959). According to Trietsch and Baker (2012), PERT remains relevant in modern project management because it provides a structured way to evaluate schedule risk, despite the emergence of more advanced decision-support systems.

The theoretical distinction between CPM and PERT lies in their treatment of time: CPM assumes certainty, while PERT explicitly models uncertainty. This distinction has led to the argument that neither method alone is sufficient for complex construction environments where both structured planning and uncertainty management are required.

2.2. Application of CPM and PERT in Construction Projects

Numerous empirical studies have demonstrated the effectiveness of CPM and PERT in improving project scheduling performance. For instance, Bagshaw (2021) emphasizes that CPM is highly effective in identifying critical activities and ensuring efficient resource utilization, while PERT is better suited for projects with uncertain durations. Similarly, Aulia and Cipta (2023) show that applying CPM–PERT can significantly reduce project duration and optimize costs by enabling better scheduling decisions.

Case studies across different construction contexts further support these findings. Sukamta et al. (2026) report that combining CPM and PERT improves scheduling accuracy and increases the likelihood of on-time project completion in housing construction. Likewise, Fauzah et al. (2024) demonstrate that integrating CPM and PERT improves alignment between planned and actual project progress, thereby reducing delays in high-rise building projects.

In industrial and maintenance projects, Hanifa et al. (2024) and Suryono and Hasbullah (2020) find that CPM–PERT analysis helps identify critical paths and improve project efficiency. These studies collectively argue that CPM and PERT are versatile tools applicable across various sectors, reinforcing their importance in construction project management.

2.3. Integration of CPM and PERT: A Complementary Approach

Recent literature increasingly advocates integrating CPM and PERT to overcome the limitations of each method when used independently. Ba'Its et al. (2020) argue that CPM provides structural clarity in scheduling, while PERT introduces probabilistic realism, making their integration essential for accurate project evaluation. Similarly, Ridwan (2025) highlights that combining both methods enhances decision-making by improving time estimation accuracy and reducing uncertainty-related risks.

From a conceptual standpoint, Itani (2023) describes the CPM–PERT integration as a hybrid framework that harmonizes deterministic and probabilistic elements, allowing project managers to adapt to dynamic project conditions. This integrated approach is particularly beneficial in construction projects, where uncertainty is inherent and unavoidable.

Moreover, Andiyan et al. (2021) demonstrate that combining CPM–PERT with other techniques, such as Critical Chain Project Management (CCPM), further enhances scheduling performance and reduces delays. These findings suggest that CPM–PERT integration serves as a foundational framework that can be extended with advanced methodologies.

2.4. Advances in Scheduling Techniques and Emerging Trends

In response to increasing project complexity, researchers have explored advanced methods to enhance traditional CPM–PERT approaches. For example, Calp and Akcayol (2018) propose using genetic algorithms to optimize scheduling in dynamic CPM–PERT networks, enabling faster, more accurate solutions for complex projects. Similarly, Agyei (2015) and Mansur Nuhu et al. (2024) use linear programming to balance time and cost trade-offs, demonstrating the potential of mathematical optimization in project scheduling.

Another emerging trend is the integration of digital technologies into project management. Wang et al. (2014) highlight the role of Building Information Modeling (BIM) combined with augmented reality (AR) in improving real-time communication and on-site decision-making. These technologies enhance the visualization and monitoring of project schedules, thereby reducing errors and improving efficiency.

Furthermore, Derbe et al. (2020) identify key research trends in construction scheduling through a scientometric review, including risk analysis, optimization models, and the adoption of advanced technologies. Their study underscores the growing complexity of project scheduling and the need for more integrated and adaptive approaches.

Despite the extensive application of CPM and PERT, several limitations persist in the existing literature. First, many studies assume the availability of detailed activity-level data, including precise dependency relationships and duration estimates. In practice, such detailed data are often unavailable, particularly in developing countries or small-scale projects, where schedules are typically presented in aggregated forms such as Work Breakdown Structures or S-curves (Maravas & Pantouvakis, 2012).

Second, while advanced methods such as genetic algorithms and linear programming offer improved accuracy, they often require high computational complexity and specialized expertise, limiting their practical applicability in real-world projects (Calp & Akcayol, 2018). This creates a gap between theoretical advancements and practical implementation.

Third, although digital technologies such as BIM and AR show promise for enhancing project scheduling, their adoption remains limited due to high implementation costs and technical barriers, particularly in developing regions (Wang et al., 2014). Finally, many empirical studies focus on specific case studies, limiting the generalizability of their findings. There is a lack of research that systematically addresses scheduling challenges under data-constrained conditions, which are common in infrastructure projects.

3. Materials and Methods

This study adopts a quantitative, descriptive approach to evaluate the schedule performance of a drainage construction project by integrating the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT). The objective is to provide a comprehensive assessment by combining deterministic and probabilistic analyses of project scheduling. CPM is employed to identify the dominant sequence of activities that determines the overall project duration, whereas PERT is used to evaluate uncertainty in activity durations and estimate the probability of completing the project within the planned timeframe. The integration of these two methods enables a more realistic evaluation of project schedules, particularly under uncertain conditions (Ba'lts et al., 2020; Trietsch & Baker, 2012).

The data used in this study are secondary data obtained from the implementation schedule of an urban drainage construction project, presented as a weekly S-curve. The schedule reflects cumulative work progress based on the Work Breakdown Structure (WBS), with a total planned duration of 180 calendar days. The project comprises six primary work packages: Construction Safety Management System, Preparation Works, Earthworks, Piling Works, Drainage Channel Construction, and Pedestrian Access Works. Due to the absence of detailed activity-level data and explicit dependency relationships, the analysis is conducted at the aggregated WBS level, a commonly adopted approach in project scheduling studies under data-constrained conditions (Maravas & Pantouvakis, 2012).

A CPM network model is developed based on the WBS to represent the logical sequence of project activities. Since detailed predecessor–successor relationships are not explicitly available, dependencies among work packages are defined based on standard construction practices. The CPM analysis is conducted by calculating time parameters using forward and backward pass techniques. The Early Start (ES) of an activity is determined as the maximum Early Finish (EF) of its preceding activities:

$$ES_j = \max(EF_i) \tag{1}$$

The Early Finish (EF) is calculated as:

$$EF = ES + D \tag{2}$$

where Drepresents the activity duration. The Late Finish (LF) is obtained as the minimum Late Start (LS) of subsequent activities:

$$LF_i = \min(LS_j) \tag{3}$$

and the Late Start (LS) is calculated as:

$$LS = LF - D \tag{4}$$

To determine schedule flexibility, the Total Float (TF) is calculated as:

$$TF = LS - ES = LF - EF \tag{5}$$

Activities with a total float equal to zero are identified as critical activities, forming the critical path that governs the overall project completion time (Moder et al., 1983). To incorporate uncertainty into the analysis, the PERT method is applied to activities located on the critical path. Each activity is evaluated using three-time estimates: optimistic (t_o), most likely (t_m), and pessimistic (t_p). The expected duration of each activity is calculated using the PERT weighted average formula:

$$t_e = \frac{t_o + 4t_m + t_p}{6} \tag{6}$$

This formulation provides a balanced estimate that emphasizes the most likely duration while accounting for uncertainty (Trietsch & Baker, 2012). The variability of activity durations is measured through variance, calculated as:

$$\sigma^2 = \left(\frac{t_p - t_o}{6}\right)^2 \tag{7}$$

The overall uncertainty of the project is represented by the standard deviation of the critical path, obtained by aggregating the variances of all critical activities:

$$\sigma_{CP} = \sqrt{\sum \sigma_i^2} \tag{8}$$

To evaluate the likelihood of completing the project within the planned duration, a probability analysis is conducted using the Z-score:

$$Z = \frac{T - t_{e,CP}}{\sigma_{CP}} \tag{9}$$

where Tdenotes the target project duration, $t_{e,CP}$represents the expected duration of the critical path, and $\sigma_{CP}$is the standard deviation of the critical path. The calculated Z-value is then used to determine the probability of on-time project completion based on the standard normal distribution.

The integration of CPM and PERT is performed sequentially: CPM first identifies the critical path, and PERT subsequently evaluates uncertainty in the dominant activities. This integrated framework provides a comprehensive evaluation of schedule performance by combining structural analysis with probabilistic assessment. The overall analytical process consists of developing the CPM network based on the WBS, identifying critical activities, applying PERT to estimate duration uncertainty, and calculating the probability of project completion.

Despite its robustness, this methodology has several limitations. The use of aggregated WBS data reduces the level of detail in activity-level analysis, and dependency relationships are based on logical assumptions rather than explicit project records. Additionally, the probabilistic assumptions in PERT rely on simplified distributions that may not fully capture real-world variability. Nevertheless, the approach remains practical and effective for evaluating schedule performance in infrastructure projects, particularly under conditions of limited data availability.

4. Results

4.1. Critical Path Method (CPM) Analysis

4.1.1. WBS-Based CPM Network Structure

The results of this study present the evaluation of the drainage construction project schedule using the integrated Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT). The analysis focuses on developing a Work Breakdown Structure (WBS)-based network, identifying the dominant project path, and assessing uncertainty in key activities that influence project completion. The CPM analysis was conducted by developing a project network at the WBS level, consisting of six main work packages. This approach was adopted because aggregated schedule data were available rather than detailed activity-level information.

The network structure represents the logical sequence of construction activities, beginning with preparation works and progressing through earthworks, piling works, drainage channel construction, and finally pedestrian access works. Parallel relationships were identified between earthworks and piling works, while construction safety management activities were positioned as supporting functions throughout the project lifecycle. This WBS-based modeling approach provides a simplified yet representative structure for evaluating schedule performance under data limitations (see Figure 1).

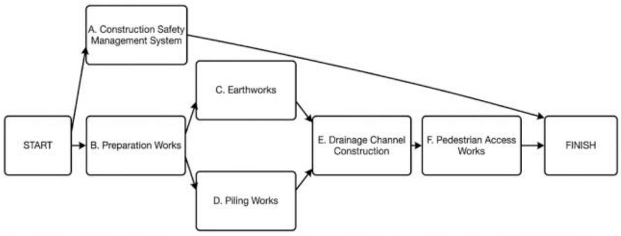

Figure 1. CPM network diagram based on work breakdown structure of the drainage construction project.

Figure 1 illustrates the Critical Path Method (CPM) network diagram developed based on the Work Breakdown Structure (WBS) of the drainage construction project. The diagram represents the logical sequence of project activities, their interdependencies, and the overall workflow from project initiation to completion. This visualization serves as a fundamental tool for identifying the dominant path and understanding how different work packages contribute to the total project duration.

The network begins with the Start node, followed by Preparation Works (B), which act as the initial prerequisite for all subsequent physical construction activities. Preparation works include site clearance, mobilization, and preliminary setup, and therefore must be completed before other technical operations can proceed. At the same time, the Construction Safety Management System (A) is shown as a supporting activity that runs in parallel with the main workflow. Although it does not directly constrain the sequence of construction activities, it plays a critical role in ensuring compliance, safety, and operational continuity throughout the project lifecycle.

After the completion of preparation works, the project transitions into two parallel activities: Earthworks (C) and Piling Works (D). These activities are executed simultaneously to optimize time efficiency, as they do not depend on each other, but both depend on the completion of preparation works. The parallel configuration in the network indicates an opportunity for schedule compression, as multiple activities can proceed concurrently without extending the total project duration.

Both earthworks and piling works converge into Drainage Channel Construction (E), which represents the core activity of the project. This convergence indicates that drainage channel construction cannot begin until both preceding activities are completed. As a result, activity E becomes a critical integration point in the network. Any delay in either earthworks or piling works will directly postpone the start of drainage channel construction, thereby affecting the overall project schedule.

Following this, the workflow proceeds to Pedestrian Access Works (F), which constitute the final stage of construction before project completion. This activity depends entirely on the completion of drainage channel construction, making it part of the final segment of the project's critical sequence. The network concludes at the Finish node, indicating the completion of all project activities. From the structure of Figure 1, the dominant (critical) path can be clearly identified as:

Preparation Works (B) → Earthworks (C) and Piling Works (D) → Drainage Channel Construction (E) → Pedestrian Access Works (F). This path represents the sequence of activities with zero total float, meaning that any delay in these activities will directly delay project completion. Among these, Drainage Channel Construction (E) is the most critical activity, as it serves as the central node that integrates preceding works and determines the start of final activities. Similarly, Pedestrian Access Works (F) acts as the completion-locking activity, meaning that delays at this stage cannot be absorbed or mitigated by other parallel activities.

In contrast, the Construction Safety Management System (A), while essential, is not part of the critical path because it operates in parallel and does not directly constrain the sequence of dependent construction activities. This distinction highlights the difference between supporting activities and time-critical activities within the project network.

4.1.2. Identification of the Project Dominant Path

Table 1 presents a structured summary of the work packages, their dependency relationships, and their roles in the project schedule, serving as the basis for the Critical Path Method (CPM) analysis. The table provides a clear classification of activities by functional role and their impact on overall project duration, thereby facilitating a deeper understanding of the project's scheduling structure.

Table 1. Summary of Work Packages and CPM Dependency Relationships

Code	Work Package	Dependency Relationship	Role in Schedule
A	Construction Safety Management System	Conducted continuously in parallel throughout project	Supporting activity
B	Preparation Works	Initiates all physical construction activities	Prerequisite activity
C	Earthworks	Follows preparation works; executed parallel with D	Critical (dominant path)
D	Piling Works	Follows preparation works; executed parallel with C	Critical (dominant path)
E	Drainage Channel Construction	Commences after completion of C and D	Most critical activity
F	Pedestrian Access Works	Begins after completion of E	Project completion (final lock)

The analysis begins with Construction Safety Management System (A), which is categorized as a supporting activity. This work package operates in parallel throughout the project lifecycle and imposes no direct constraints on the sequence of construction activities. Although it does not lie on the critical path, its continuous implementation is essential for ensuring compliance with safety standards and minimizing operational risks. Its classification as a supporting activity highlights that not all project components directly influence schedule duration, even though they remain critical from a managerial and regulatory perspective.

The next work package, Preparation Works (B), is identified as a prerequisite activity, marking the transition from project initiation to physical construction. As the initial stage of execution, preparatory work establishes the necessary conditions for subsequent activities, including site readiness, resource mobilization, and preliminary arrangements. Because all major construction activities depend on its completion, any delay in this phase will propagate throughout the project, making it a key determinant of schedule initiation.

Following the preparatory works, the project progresses to Earthworks (C) and Piling Works (D), both of which are classified as part of the dominant path. These activities are executed after the completion of preparation works and are designed to proceed in parallel. The parallel relationship between earthworks and piling works reflects an effort to optimize time efficiency by allowing simultaneous execution of independent tasks. However, despite their parallel nature, both activities are critical because they jointly determine the start of the subsequent work package. This dual dependency structure indicates that delays in either earthworks or piling work will directly affect the next stage, underscoring their importance in maintaining schedule continuity.

The convergence of earthworks and piling works leads to Drainage Channel Construction (E), which is identified in Table 1 as the most critical activity in the project schedule. This classification is justified by its position as a central node that integrates prior activities and governs the transition to the project's final stage. Since drainage channel construction can only begin after both earthworks and piling works are completed, it serves as a bottleneck in the network. Any delay in this activity has a direct, unavoidable impact on the overall project duration, making it the primary focus of schedule control and risk management.

Subsequently, the project advances to Pedestrian Access Works (F), which are categorized as the project completion lock. This designation indicates that this activity represents the final stage required to achieve project completion. Unlike earlier activities, there are no subsequent tasks that can absorb delays at this stage. Therefore, any delay in pedestrian access works will directly delay project completion. This highlights its critical role in determining the project's final delivery timeline.

The result reveals a structured hierarchy of activities within the project schedule, distinguishing between supporting, prerequisite, dominant, and critical roles. The classification demonstrates that while some activities contribute indirectly to project success, others, particularly those on the dominant path, have a direct and decisive influence on project duration. The identification of Drainage Channel Construction (E) as the most critical activity and Pedestrian Access Works (F) as the completion-locking stage underscores the importance of focusing managerial attention on these work packages.

Furthermore, the dependency relationships outlined in Table 1 highlight the presence of both sequential and parallel workflows within the project. While parallel activities such as earthworks and piling work can improve efficiency, their convergence into a single critical activity can introduce bottlenecks. This duality reflects the inherent complexity of construction scheduling, in which optimization opportunities must be carefully balanced with dependency constraints. The results emphasize that effective schedule control should prioritize activities along the dominant path, particularly those with integration and completion-locking roles. This analysis forms the foundation for subsequent uncertainty evaluation using PERT, in which the variability of critical activities is further assessed to determine the reliability of completing the project within the planned duration.

4.2. Schedule Uncertainty Analysis using PERT

4.2.1. Dominant Activities in PERT Analysis

Figure 2 presents the PERT-based probabilistic network diagram, focusing on the dominant activities identified in the CPM analysis: Drainage Channel Construction (E) and Pedestrian Access Works (F). Unlike the CPM network in Figure 1, which represents the full project structure, this diagram simplifies the network by isolating the most critical activities that directly determine project completion. This targeted approach allows for a more detailed analysis of uncertainty and variability in the activities that have the greatest impact on schedule performance.

The diagram begins with the Start node, followed by activity E (Drainage Channel Construction), which is represented using three-time estimates: optimistic (t_o), most likely (t_m), and pessimistic (t_p). The inclusion of these three parameters reflects the probabilistic nature of PERT, in which activity durations are treated as random variables rather than fixed values. This is particularly relevant for drainage channel construction, which is influenced by factors such as weather conditions, soil variability, site accessibility, and interactions with existing infrastructure.

Following activity E, the network proceeds to activity F (Pedestrian Access Works), which is also evaluated using three-point estimation. Similar to drainage channel construction, this activity is subject to uncertainty due to finishing requirements, coordination constraints, and potential delays in preceding work. As the final activity before project completion, any variation in its duration directly affects the overall project timeline.

The sequence concludes at the Finish node, indicating that the completion of activity F marks the completion of the entire project. The linear structure of the PERT network emphasizes that these two activities form the final segment of the critical path, and therefore their combined duration determines the final project completion time.

The primary insight from Figure 2 is that uncertainty is concentrated in a limited number of dominant activities, rather than being uniformly distributed across all project tasks. By focusing the PERT analysis on activities E and F, the study highlights that variability in these activities has a disproportionately large impact on the overall project schedule. This approach aligns with the principle that effective risk analysis should prioritize critical-path activities, as they represent the main sources of schedule risk.

Furthermore, the use of three-point estimation enables the calculation of the expected duration (t_e), variance, and standard deviation for each activity. These values are then aggregated to determine the overall uncertainty of the critical path. The results indicate that the expected duration of the critical path is likely to exceed the deterministic estimate obtained from CPM, suggesting that the original project schedule may underestimate the actual time required for completion.

The probabilistic nature of the PERT analysis also allows for estimating the probability of completing the project within the planned 180-day duration. The results show that this probability is significantly influenced by the variability of drainage channel construction, which emerges as the most uncertain and impactful activity. Consequently, even small deviations in the duration of this activity can substantially reduce the likelihood of on-time project completion.

Another important implication of Figure 2 is the identification of risk concentration at the project's final stages. Since both activities E and F are located at the end of the project network, there is minimal opportunity for schedule recovery once delays occur. This lack of buffer highlights the importance of proactive planning, continuous monitoring, and risk mitigation strategies during these stages.

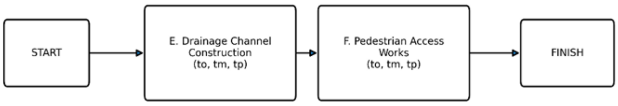

Figure 2. PERT-Based Probabilistic Network Diagram

Figure 2 demonstrates that integrating PERT into the analysis provides a deeper understanding of schedule uncertainty by quantifying the variability of critical activities. While CPM identifies the structural importance of activities E and F, PERT reveals the extent to which uncertainty in these activities can affect project completion. The results emphasize that effective project management should focus not only on identifying critical activities but also on managing the uncertainty associated with them, particularly in the final phases of construction projects.

4.2.2. Duration Estimates and Uncertainty of Dominant Activities

Table 2 presents the three-point duration estimates used in the Program Evaluation and Review Technique (PERT) analysis for the dominant activities identified in the CPM results, namely Drainage Channel Construction (E) and Pedestrian Access Works (F). These activities were selected because they are on the critical path and therefore have a direct, decisive influence on the overall project completion time.

Table 2. Estimated Durations of Dominant Activities for PERT Analysis

Code	Work Package	Optimistic Time (to)	Most Likely Time (tm)	Pessimistic Time (tp)
E	Drainage Channel Construction	Shorter than planned duration	Planned duration	Longer than planned duration
F	Pedestrian Access Works	Shorter than planned duration	Planned duration	Longer than planned duration

The table categorizes activity durations into three scenarios: optimistic time (t_o), most likely time (t_m), and pessimistic time (t_p). The optimistic time represents the shortest possible duration under ideal conditions, where all resources are available, environmental conditions are favorable, and no disruptions occur. In contrast, the pessimistic time reflects the longest possible duration under unfavorable conditions, such as adverse weather, technical difficulties, or coordination delays. The most likely time corresponds to the planned or expected duration under normal working conditions.

For both activities E and F, the optimistic duration is shorter than the planned duration, while the pessimistic duration is longer, indicating variability around the baseline schedule. This qualitative representation suggests that the planned duration (t_m) serves as a central estimate, with potential deviations on both sides depending on project conditions. Such a structure is consistent with the fundamental assumption of PERT that activity durations follow a probabilistic distribution rather than a fixed value.

Among the two activities, Drainage Channel Construction (E) is characterized by greater uncertainty than Pedestrian Access Works (F). This is primarily due to its technical complexity and sensitivity to external factors, including soil conditions, groundwater levels, weather variability, and interference with existing infrastructure. As a core construction activity, it involves multiple sub-processes and coordination among various resources, increasing the likelihood of deviations from the planned schedule. Consequently, the range between optimistic and pessimistic durations for this activity is expected to be wider, contributing significantly to overall project uncertainty.

Similarly, Pedestrian Access Works (F) also exhibits variability, although to a relatively lesser extent. As a finishing activity, it depends heavily on the timely completion of preceding works, particularly drainage channel construction. Any delays in activity E will directly shift the start time of activity F, potentially amplifying the overall project delay. Additionally, finishing works often involve aesthetic, accessibility, and safety considerations, which may introduce further adjustments and minor delays.

The use of three-point estimates in Table 2 enables the calculation of the expected duration (t_e) for each activity using the PERT weighted average formula (6). This calculation provides a more realistic estimate by giving greater weight to the most likely duration while still accounting for uncertainty. Furthermore, the variability of each activity is quantified through the variance (equation 7).

These statistical measures are essential for evaluating the overall uncertainty of the critical path, as they enable aggregation of variability across dominant activities. The results derived from Table 2 indicate that uncertainty is not uniformly distributed across project activities but is concentrated in critical-path activities, particularly drainage channel construction. This concentration of uncertainty has important implications for project management, suggesting that efforts to improve schedule reliability should focus on reducing variability in these key activities.

Moreover, the presence of both optimistic and pessimistic scenarios underscores the need for risk-informed scheduling, in which project managers consider multiple possible outcomes rather than relying solely on deterministic estimates. By incorporating variability into the analysis, PERT provides a more comprehensive understanding of schedule performance and supports more effective decision-making.

This study demonstrates that the durations of dominant activities exhibit significant variability, which directly affects the reliability of the project schedule. The findings reinforce the importance of integrating probabilistic analysis into project scheduling and highlight the need for focused control and risk-mitigation strategies for critical activities, particularly those in the final stages of the project.

5. Discussion

The findings of this study demonstrate that integrating the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT) provides a robust, comprehensive framework for evaluating schedule performance in drainage construction projects. The CPM analysis reveals that project completion is governed by a clearly defined dominant path comprising preparation works, earthworks and piling works, drainage channel construction, and pedestrian access works. This result is consistent with the foundational concept of CPM, which emphasizes that activities with zero float directly determine project duration and therefore require strict monitoring and control (Kelley & Walker, 1959; Bagshaw, 2021).

A critical insight from the analysis is the identification of drainage channel construction as the most influential activity within the project network. Its role as a convergence point for preceding activities positions it as a bottleneck that significantly affects downstream processes. This finding aligns with previous studies indicating that technically complex and resource-intensive construction activities tend to dominate project schedules and are highly susceptible to delays (Fauzah et al., 2024; Suryono & Hasbullah, 2020). Furthermore, pedestrian access works, as the final stage of the project, function as a completion-locking activity, reinforcing the argument that delays occurring in the final phases of construction have a direct and unavoidable impact on overall project delivery (Sukamta et al., 2026).

While CPM effectively identifies the structural importance of activities, it does not account for uncertainty in activity durations. The PERT analysis complements this limitation by incorporating probabilistic time estimates, revealing that the expected duration of the critical path tends to exceed the deterministic estimate derived from CPM. This finding supports the argument that traditional scheduling methods based on fixed durations may underestimate project timelines, particularly in complex construction environments characterized by uncertainty (Trietsch & Baker, 2012; Hajdu & Bokor, 2014). The observed discrepancy between deterministic and probabilistic results highlights the importance of integrating uncertainty analysis into project scheduling practices.

The results also indicate that uncertainty is concentrated in dominant activities, particularly in drainage channel construction. This concentration suggests that not all project activities contribute equally to schedule risk; rather, a small subset of critical-path activities accounts for most of the schedule risk. This observation is consistent with the findings of Hajdu and Bokor (2014), who emphasize that the accuracy of duration estimation for critical activities is more important than the selection of probability distributions in PERT analysis. Consequently, improving the reliability of duration estimates for key activities can significantly enhance overall schedule performance.

From a managerial perspective, integrating CPM and PERT provides a dual analytical advantage. CPM provides a clear, structured representation of activity dependencies, enabling project managers to identify critical tasks and allocate resources efficiently. In contrast, PERT introduces a probabilistic dimension that allows for the evaluation of schedule uncertainty and the estimation of completion probabilities. This combined approach enhances decision-making by enabling project managers to anticipate potential delays and implement proactive mitigation strategies. Similar conclusions have been reported by Ba'Its et al. (2020) and Ridwan (2025), who note that integrating deterministic and probabilistic methods improves scheduling accuracy and reduces the risk of project delays.

However, the application of the CPM–PERT approach in this study also reveals several limitations. First, the analysis is conducted at the Work Breakdown Structure (WBS) level, using aggregated schedule data rather than detailed activity-level information. While this approach is practical and reflects real-world conditions, it may limit the precision of dependency modeling and duration estimation (Maravas & Pantouvakis, 2012). Second, the PERT method assumes simplified probabilistic distributions for activity durations, which may not fully capture the complexity of uncertainties encountered in construction projects. These limitations suggest that the CPM–PERT framework should be viewed as a strategic evaluation tool rather than a fully precise predictive model.

In comparison with recent developments in project scheduling, such as optimization techniques and digital technologies, the CPM–PERT approach offers a balance between analytical rigor and practical applicability. Advanced methods, including genetic algorithms (Calp & Akcayol, 2018) and linear programming approaches (Agyei, 2015; Mansur Nuhu et al., 2024), have demonstrated improved optimization capabilities but often require sophisticated computational tools and expertise. Similarly, integrating Building Information Modeling (BIM) with augmented reality (AR) has been shown to enhance real-time project monitoring and communication (Wang et al., 2014). Nevertheless, the adoption of these advanced methods remains limited in many construction contexts due to resource and technical constraints. In contrast, the CPM–PERT approach remains accessible, adaptable, and widely applicable, particularly in developing environments.

The contribution of this study lies in demonstrating that a WBS-based CPM–PERT integration can effectively evaluate schedule performance even under conditions of limited data availability. This finding addresses a notable gap in the literature, where most studies assume the availability of detailed activity-level data and complete dependency structures. By adapting CPM–PERT analysis to aggregated schedules, this study extends its applicability to real-world infrastructure projects and provides a practical framework for project managers dealing with data constraints.

6. Conclusions

This study evaluates the schedule performance of a drainage construction project by integrating the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT) using a Work Breakdown Structure (WBS)-based approach. The findings demonstrate that the project duration is primarily governed by a dominant path consisting of preparation works, earthworks and piling works, drainage channel construction, and pedestrian access works. Among these, drainage channel construction and pedestrian access works are identified as the most critical activities, as they directly determine the project's completion and are highly sensitive to delays.

The application of CPM successfully provides a clear structural representation of activity dependencies and identifies the critical path that governs project duration. However, the results also show that deterministic scheduling alone is insufficient to capture the inherent variability of construction projects. The integration of PERT addresses this limitation by incorporating uncertainty through probabilistic time estimates, indicating that the expected project duration tends to exceed the planned schedule. This indicates that reliance on fixed-duration assumptions may lead to an underestimation of the time required to complete the project.

Furthermore, the study highlights that uncertainty is concentrated in dominant activities, particularly drainage channel construction, which is influenced by factors such as site conditions, weather variability, and technical complexity. As a result, the reliability of completing the project within the planned 180 calendar days is highly dependent on the effectiveness of schedule control and risk management strategies applied to these critical activities.

From a practical perspective, integrating CPM and PERT provides a comprehensive framework for project managers to improve schedule performance. By combining deterministic and probabilistic analyses, this approach enables better identification of critical activities, more accurate project duration estimates, and enhanced anticipation of potential delays. Consequently, project managers are encouraged to prioritize monitoring and resource allocation on dominant-path activities and to implement proactive risk mitigation strategies, particularly in the final stages of construction.

Despite its contributions, this study is limited to using aggregated WBS-based schedule data, which may reduce the level of detail in activity relationships and duration estimation. Therefore, future research is recommended to incorporate more detailed activity-level data and to integrate CPM–PERT analysis with advanced methods such as simulation modeling or digital technologies to improve accuracy and applicability.

In conclusion, this study demonstrates that a WBS-based integration of CPM and PERT is an effective and practical approach for evaluating schedule performance in infrastructure construction projects under conditions of limited data availability. The findings provide valuable insights for both researchers and practitioners to improve project time control, enhance decision-making, and reduce the risk of schedule delays in complex construction environments.

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