J-Researchers

Journal of Civil Engineering Researchers

Journal homepage: www.journals-researchers.com

Integrating Weighted Delay Index (WDI) with Dynamic Critical Path Analysis for Enhanced Delay Assessment in Construction Projects

Mohsen Asgharinia [a,*], Amin Moradi [b]

[a] *Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran*
[b] *Amirkabir University of Technology, Tehran, Iran .*

ABSTRACT

Project delays remain one of the most persistent challenges in construction management, often leading to substantial cost overruns and disputes. Conventional scheduling and delay analysis techniques—such as Critical Path Method (CPM), Earned Value Management (EVM), and Extension of Time (EOT) methods—typically overlook the unequal importance of activities and the dynamic shifts in project execution. This study introduces the Weighted Delay Index (WDI), a novel metric that integrates activity-specific weights with dynamic critical path analysis to provide a more precise evaluation of delay severity. Activity weights were derived using the Analytical Hierarchy Process (AHP) across four key dimensions: time, cost, risk, and technical impact. The methodology was validated on multiple construction projects through comparison with Time Impact Analysis (TIA). Results show that project duration is the dominant predictor of delay, while WDI serves as a strong diagnostic signal, highlighting activities whose delays disproportionately influence project outcomes. Workforce intensity further moderates delay severity, with higher intensity reducing delay risks. By combining AHP-based weighting with dynamic scheduling, the WDI offers project managers a practical early-warning and prioritization tool that surpasses aggregated delay measures. The findings contribute to both theory and practice by bridging deterministic scheduling with activity-sensitive delay assessment and by outlining directions for future enhancement.

ARTICLE INFO

Received: August 18,2025
Accepted: December 12,2025

Keywords:
Construction project
Delays
Weighted Delay Index
Dynamic Critical Path Method
Extension of Time

DOI: 10.61186/JCER.8.1.47
DOR: 20.1001.1.22516530.1399.11.4.1.1

1.Introduction

Project scheduling plays a pivotal role in ensuring the successful completion of construction and infrastructure projects, particularly in environments where cost overruns and time delays are frequent. The Critical Path Method (CPM) has long been recognized as a fundamental tool for project planning and control. However, the traditional CPM is often criticized for its static nature, since it does not adequately account for dynamic updates in activity delays and changes in network logic during project execution.

In recent decades, various indices have been proposed to measure schedule performance and to assess the impact of delays, such as the Schedule Performance Index (SPI), the Earned Schedule (ES), and different delay analysis methods. Despite their usefulness, these approaches frequently neglect the relative importance of individual activities within the project network. In practice, not all activities contribute equally to project objectives: some

---

[*] Corresponding author.; e-mail:mohsen76a@aut.ac.ir, email: moradi_amin85@yahoo.com

activities are cost-intensive, risk-sensitive, or strategically critical, while others have a relatively marginal impact.

To bridge this gap, the Weighted Delay Index (WDI) is introduced as a novel metric that combines activity weighting with dynamic critical path analysis. The WDI provides a more nuanced measure of delay severity by integrating both the magnitude of activity delays and their relative significance to overall project performance. Unlike traditional indices, WDI is flexible and can incorporate multiple weighting criteria—such as cost, resource allocation, or risk exposure—allowing for a context-specific prioritization of activities.

This study develops the WDI framework, applies it to selected case studies, and evaluates its predictive ability in identifying critical delay sources and forecasting project-level impacts. The proposed index aims to provide project managers with an early-warning tool that not only quantifies delay intensity but also highlights which delayed activities warrant immediate managerial attention.

2.Literature Review

The assessment of project delays has been a long-standing research topic in construction management. Traditional methods of delay analysis are typically grounded in deterministic scheduling techniques. The Critical Path Method (CPM), first introduced in the late 1950s, remains one of the most widely used techniques for identifying activity sequences that directly determine project duration. However, CPM assumes a fixed project network and deterministic activity durations, which limits its applicability under conditions of uncertainty and dynamic project environments.

To address these limitations, several extensions have been proposed. The concept of the dynamic critical path was developed to reflect real-time updates in project execution, recognizing that the critical path may shift as activities are delayed or accelerated [1]. Parallel to this, the field of schedule performance measurement introduced indices such as the Schedule Performance Index (SPI) under the Earned Value Management framework [2]. Although SPI and Earned Schedule provide valuable insight into overall schedule adherence, they tend to aggregate delays at the project level, without differentiating between the relative significance of individual activities.

More recent studies emphasize the importance of activity weighting by factors such as cost, resources, and risk. Activity Criticality Indices have been developed in probabilistic schedule risk analysis to quantify the likelihood of an activity being on the critical path [3]. Similarly, weighted performance indices have been applied in cost and schedule control to reflect project priorities. Nevertheless, these approaches remain fragmented and have not been fully integrated into delay analysis at the activity level.

In response, researchers have explored more dynamic and flexible scheduling approaches. Vanhoucke (2013) emphasized the limitations of static CPM under uncertainty and proposed dynamic scheduling with risk-informed sensitivity analysis [4]. The integration of EVM with CPM has been shown to provide a more comprehensive view of project performance, combining schedule adherence with resource and cost tracking [5]. Further, Purushothaman et al. (2025) examined influential factors in dynamic scheduling environments and their impact on real-time planning [6], while the Schedula Anima platform demonstrated advanced visualization and rescheduling capabilities for dynamic Gantt charts [7]. Similarly, Kim et al. (2020) proposed the extended resource-constrained CPM (eRCPM), which accounts for resource dependencies in critical path analysis [8], and Chaudhary & Meshram (2025) compared CPM, RCS, and RCPM under resource constraints, highlighting the need for flexible weighting and dynamic analysis [9].

In addition to methodological improvements, researchers have increasingly turned toward data-driven and probabilistic approaches. For instance, Gondia et al. (2020) applied machine learning algorithms to predict delay risks in construction projects and demonstrated higher accuracy than traditional regression models [10]. Building on this, Çevikbaş et al. (2022) proposed a modified scheduling and delay-analysis method that better reflects actual project updates and provides more reliable insights for delay claims [11]. From a probabilistic perspective, Bektaş et al. (2021) developed the Integrated Probabilistic Delay Analysis Method (IPDAM), which estimates the likely outcomes of delay disputes and enhances fairness in claims resolution [12]. More recently, Alsulamy (2025) employed advanced machine learning models (CatBoost, XGBoost, LGBM) to predict delay risks in Saudi Arabian construction projects, highlighting the growing role of AI in proactive delay management [13].

The gap identified in the literature is twofold:

1. Existing delay indices lack sensitivity to the relative importance of activities within the network.
2. Most methods fail to combine activity weighting with the dynamic nature of the critical path, limiting their predictive and diagnostic power.

To address this gap, the current study introduces the Weighted Delay Index (WDI), which simultaneously accounts for activity importance and dynamic critical path analysis. This dual consideration positions WDI as a more robust and practical tool for real-time delay assessment and prioritization in complex projects.

For these problems, analytical, semi-analytical, and numerical methods are used in time and frequency domains [7,8].

The seismic source, soil complexity, and analysis goals determine the model's dimensionality from 1D to 3D, which affects soil behavior under seismic loads [8-12].

Damping is crucial in site response analysis for capturing energy dissipation mechanisms within soil layers under seismic loads. It significantly reduces seismic energy, affecting both the amplitude and duration of surface ground motion. By incorporating damping into models, predictions of soil behavior during seismic events become more accurate, reflecting the natural energy loss from hysteresis and viscous behavior in soil materials [7,12]. Properly calibrated damping parameters yield more realistic ground motion estimates, particularly vital for high-intensity seismic events [13]. Park and Hashash [14] highlight the importance of precise damping modeling in the context of non-linear time domain site response analysis.

3.Methodology

The methodological framework of this study consists of four main stages: (1) defining activity weights, (2) calculating effective delays under dynamic critical path conditions, (3) developing the Weighted Delay Index (WDI), and (4) validating the index through case studies. Figure 1 illustrates the overall research workflow.

3.1. Defining Activity Weights

Project activities are not equally significant to project success. In order to capture their relative importance, a normalized weight is assigned to each activity i in the network. The weight can be determined using multiple approaches, depending on project context:

Cost-based weighting

$w_i = \frac{C_i}{\sum_{j=1}^{N} C_j}$:

$C_i$is the direct cost of activity

Resource-based weighting:

$w_i = \frac{R_i}{\sum_{j=1}^{N} R_j}$

$R_i$represents allocated man-hours or equipment-hours.

Risk-based weighting: $w_i = \frac{I_i \times P_i}{\sum_{j=1}^{N} (I_i \times P_i)}$

$I_i$is the probability of delay and P_i is the potential impact of activity

Multi-criteria weighting (hybrid):

$$w_i = \alpha . \frac{C_i}{\sum_{j=1}^{N} C_j} + \beta . \frac{R_i}{\sum_{j=1}^{N} R_j} + \gamma . \frac{Q_i}{\sum_{j=1}^{N} Q_j}, \alpha + \beta + \gamma = 1$$

$Q_i$is expert-based judgment (e.g., AHP scores).

For all approaches, the normalization condition applies

$$\sum_{i=1}^{N} w_i = 1, w_i \geq 0$$

Figure 1 Methodology Flowchart

3.2. Dynamic Critical Path and Effective Delay Calculation

Unlike traditional CPM, the dynamic critical path reflects real-time updates of the network as activities experience delays. In each monitoring period t, the schedule is recalculated to identify the current set of critical activities. For each activity *i*, the observed delay is defined as:

$$Delay_i(t) = ActualFinish_i(t) - BaselineFinish_i$$

However, not all observed delays propagate to the project finish. To capture only the portion of delay that affects the project duration, the effective delay is defined as:

$$\Delta_i(t) = \max\{0, Delay_i(t)\} - TF_i(t)$$

Where $TF_i(t)$ is the updated total float of activity i at time t This ensures that activities delayed within their available float do not contribute to the WDI.

3.3. Weighted Delay Index (WDI)

The WDI quantifies the severity of project delays by combining activity weights with effective delays. Two versions of WDI are proposed:

Dimensionless WDI (ratio-based):

$$s_i(t) = \frac{\Delta_i(t)}{D_i}, WDI(t) = \sum_{i=1}^{N} w_i . s_i(t)$$

Where D_i is the planned duration of activity *i* This yields a normalized index between 0 and 1.

Time-scaled WDI (days-based):

$$WDI_{days}(t) = \sum_{i=1}^{N} w_i . \Delta_i(t)$$

which expresses the weighted delay directly in time units (e.g., days).

3.4. Project-Level Delay Estimation

The overall project delay at time *t* is determined by recalculating the updated project finish date:

$$\Delta T_{\Pr oject}(t) = Finish_{updated}(t) - Finish_{baseline}$$

Additionally, the utilization of project delay allowance (buffer) is computed as:

$$BufferUsed(t)\% = \frac{\Delta T_{Project}(t)}{D_{allow}} \times 100$$

D_{allow}

Where D_{allow} represents the contractual or probabilistic schedule buffer.

3.5. Algorithmic Procedure

The computational procedure of WDI is summarized as follows:

Input baseline schedule (activities, durations, dependencies , costs/resources/risks).

Assign normalized weights w_i based on the selected weighting method.

Update schedule at monitoring period *t*: record actual progress, recalculate floats, and identify the dynamic critical path.

Compute effective delays

Calculate WDI:

Dimensionless form: $WDI(t) = \sum_{i=1}^{N} w_i . \frac{\Delta_i}{D_i}$

Time-scaled form:

$WDI_{days}(t) = \sum_{i=1}^{N} w_i . \Delta_i$

WDI_{dim}

Recalculate project finish and compare with baseline to compute

$\Delta T_{\Pr oject}(t)$

Report results: highlight high-contributing activities, evaluate WDI trends, and compare with project-level delay.

3.6. Case Study Design

To validate the proposed WDI, the methodology is applied to multiple case studies of real-world construction projects. The case studies are selected to cover:

1. Projects of different sizes and complexity levels,
2. Projects with both resource-driven and cost-driven priorities,
3. Projects with documented baseline and actual progress data.

For each case study, the following analyses are performed:

4. Application of WDI framework at regular monitoring intervals.
5. Comparison of WDI outputs with actual project delays.
6. Sensitivity analysis of different weighting schemes (cost, resource, risk, hybrid).
7. Evaluation of WDI as an early-warning indicator by correlating its trends with observed project delay outcomes.

4. EOT Methodes

4.1. As-Planned vs. As-Built (APAB) Method

The As-Planned vs. As-Built method is one of the simplest EOT approaches, where the contractor's original baseline schedule is compared against the actual as-built progress to determine delays. In this method, the total delay to project completion is attributed by visually or quantitatively comparing planned versus actual progress. While easy to apply and requiring minimal data, the method does not account for the dynamic interplay of concurrent delays, float ownership, or critical path changes during execution [14]. Its simplicity often favors contractors because it captures maximum completion delay but may exaggerate entitlement, leading to disputes [15].

4.2. Impacted As-Planned (IAP) Method

The Impacted As-Planned method works by inserting excusable delay events directly into the original baseline program to see how completion shifts. Essentially, each delay is modeled as an activity in the planned schedule, and its effect on the project completion date is measured. This method assumes the baseline schedule is realistic and critical paths do not change significantly during execution. It is advantageous for its forward-looking, predictive capability but often criticized for ignoring the reality of actual progress, making it more favorable to contractors and less defensible in disputes [16].

Table 1. Project Case Studies

Project_ID	Project Title	Project Type	Location	Finish Date	Delay - TIA	sum_WDI_Delay	mean_WF	sum_duration_days	mean_WDI
Case Study_1	GRVE Pipe Line in HOSCO	EPC-Infrastructure	Iran-Bandar Abbas	May-25	37	15.401563	0.101538	70	3.992
Case Study_2	PE Pipe Line in HOSCO	EPC-Infrastructure	Iran-Bandar Abbas	May-25	71	26.018603	0.141538	130	3.992
Case Study_3	CS Pipe Line in HOSCO	EPC-Infrastructure	Iran-Bandar Abbas	May-25	83	61.60236	0.196151	149	3.917
Case Study_4	Steel Pipe Rack in HOSCO	EPC-Infrastructure	Iran-Bandar Abbas	May-25	61	55.786214	0.096526	105	4.9475
Case Study_5	Building Manhole in HOSCO	EPC-Infrastructure	Iran-Bandar Abbas	May-25	46	35.438983	0.024336	92	3.7206
Case Study_6	Construct Monorail Beam in HOSCO	EPC-Infrastructure	Iran-Bandar Abbas	May-25	44	30.745028	0.074599	86	3.3923
Case Study_7	Demolish Silo in GolGohar	C-Building	Iran-Kerman	Jul-24	115	80.333499	0.048763	207	3.8645
Case Study_8	Demolish Silo in GolGohar	C-Building	Iran-Kerman	Jul-24	69	43.576979	0.089968	126	3.3094
Case Study_9	Supply Gas Pipe Line in Babol	PC-Piping	Iran-Babol	Nov-24	48	42.356859	0.067114	83	5.1114
Case Study_10	Soil Excavation in Golshahr Complex	EPC-Geotechnic	Iran-Tehran	Dec-22	23	9.178113	0.053591	46	4.1253
Case Study_11	Soil Improvement in Hamedan	EPC-Geotechnic	Iran-Hamedan	Sep-23	86	66.708022	0.104945	164	4.1028
Case Study_12	Soil Improvement in Bandar Abbas	EPC-Geotechnic	Iran-Bandar Abbas	Oct-22	38	33.585098	0.137181	76	3.7236
Case Study_13	Fire Fighting System in Bahonar Port	PC-Mechanical	Iran-Bandar Abbas	Sep-21	82	49.003804	0.150584	139	3.769
Case Study_14	Fire Alarm System in Nowshahr Port	PC-Electrical	Iran-Nowshahr	Dec-23	103	59.642154	0.136563	175	3.4965
Case Study_15	Fire Alarm System in Boushehr Port	PC-Electrical	Iran-Boushehr	Dec-23	51	29.854627	0.06019	91	3.8886
Case Study_16	Fire Fighting System in Hormoz Port	PC-Mechanical	Iran-Bandar Abbas	Dec-23	111	84.549222	0.138082	201	3.9568
Case Study_17	Fire Alarm System in Rajaei Port	PC-Electrical	Iran-Bandar Abbas	Apr-18	70	69.232659	0.198232	141	4.9228
Case Study_18	Fencing in Petro-Ofin Site	PC-Building	Iran-Mahshahr	Aug-21	86	66.987621	0.124588	169	4.0522
Case Study_19	Motahari Building	EPC-Building	Iran-Tehran	Apr-20	57	52.060706	0.094086	106	4.2143
Case Study_20	Soil Excavation in Farmanieh Complex	EPC-Geotechnic	Iran-Tehran	May-19	51	42.132003	0.093512	89	4.5492
Case Study_21	Piling in Haghani Port	PC-Offshore	Iran-Bandar Abbas	Oct-22	59	53.754572	0.103617	125	4.5812
Case Study_22	Piling in Hormoz Port	PC-Offshore	Iran-Bandar Abbas	Oct-22	15	14.673827	0.120256	32	4.1777

4.3. Collapsed As-Built (CAB) or "But-For" Method

The Collapsed As-Built, or "But-For" method, is the reverse of the IAP approach. Here, the as-built schedule is reconstructed and then excusable delays are hypothetically removed ("collapsed") to determine when the project would have been completed but for those delays. This method is retrospective and data-intensive, requiring accurate as-built records. It is often seen as favorable to owners since it can filter out contractor-caused delays and focus on the true impact of excusable delays (Braimah, 2013). However, it may be biased if as-built data lacks accuracy, leading to contentious results.

4.4.Time Impact Analysis (TIA)

Time Impact Analysis is widely regarded as one of the most robust and contractually accepted methods for EOT assessment. It involves inserting delay events into the most recent accepted schedule update at the time of the event and analyzing the impact on project completion. This allows for a contemporaneous and incremental analysis of each delay in real time, preserving the evolving critical path. TIA provides a balanced view that benefits both contractors and owners, though it is highly data-driven and requires reliable schedule updates, which can be resource-intensive [17].

4.5. Windows Analysis (or Time-Slice Analysis)

Windows Analysis divides the project into “time windows” (e.g., monthly or quarterly) and compares planned versus actual progress within each period to determine critical delays and their causes. By examining the evolution of the critical path over time, this method accounts for concurrent delays and shifting responsibilities. It is considered one of the fairest and most accurate approaches, though it demands detailed, reliable updates and often requires advanced scheduling software [18].Owners and courts often prefer this method for its balanced and transparent view.

Table 2
Summary Comparison of EOT Methods

Method	Basis	Advantages	Limitations
As-Planned vs As-Built	Simplistic comparison	Fast and easy	No causation, concurrency, or logic update
Impacted As-Planned	Baseline + fragnets	Simple, illustrates causation	Hypothetical, ignores actual progress
Time Impact Analysis	Incremental updates	Dynamic, causally robust	Data-heavy, complex and time-consuming
Collapsed As-Built	Remove delays from actual	Real execution, legal clarity	Depends on subjective reconstruction
Window Analysis	Slice-by-slice updates	Captures evolution of schedule	Needs frequent updates, risk of oversight

5. Analytical Hierarchy Process (AHP) for Criteria Weighting

In order to determine the relative importance of the main criteria affecting delay analysis in construction projects, the Analytical Hierarchy Process (AHP) was employed. Four principal criteria were selected based on literature review and expert consultation:

1. Time – reflecting the significance of timely project completion.
2. Cost – representing budgetary and financial pacts.
3. Risk – covering contractual, managerial, and technical risks associated with delays.
4. Technical/Quality – denoting engineering performance, design accuracy, and quality compliance.

5.1. Pairwise Comparison Matrix

The pairwise comparison matrix was constructed according to Saaty’s fundamental scale (1–9). Expert judgments were simulated to represent a consensus prioritization where time was considered the most critical criterion, followed by cost, then risk, and finally technical considerations. The constructed comparison matrix is shown in Table 33.

Table 3
Pairwise comparison matrix of criteria

Criteria	Time	Cost	Risk	Technical
Time	1	3	4	5
Cost	1/3	1	2	4
Risk	1/4	1/2	1	3
Technical	1/5	1/4	1/3	1

5.2. Weight Derivation

The principal eigenvector method was used to normalize the matrix and obtain the priority weights of each criterion. The results are presented in Table 4.

Table 4
AHP weights of the main criteria

Criterion	Weight	Rank
Time	0.5506	1
Cost	0.2639	2
Risk	0.1366	3
Technical	0.0489	4

The results indicate that time (55.06%) is by far the most important consideration in delay analysis, followed by cost (26.39%), risk (13.66%), and technical factors (4.89%).

5.3. Consistency Test

To validate the reliability of the judgments, the Consistency Index (CI) and Consistency Ratio (CR) were calculated as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1} = \frac{4.1179-4}{3} = 0.0393$$

$$CR = \frac{CI}{RI} = \frac{0.0393}{0.90} = 0.0437$$

Where RI is the Random Index for n=4 (RI = 0.90).
Since CR = 0.0437<0.10, the judgments are consistent and acceptable.

5.4. Interpretation

The AHP results emphasize that project delays are primarily perceived and analyzed through the lens of time impact (schedule overrun), with cost consequences being secondary, and risk/technical considerations playing smaller roles. These weights will serve as the input coefficients for the proposed Weighted Delay Index (WDI) model in the subsequent stage of the study.

5.5. Integration of AHP Weights into the Weighted Delay Index (WDI)

The AHP-derived weights were incorporated into the Weighted Delay Index (WDI) framework to quantify the relative significance of delays across project activities. The WDI model accounts for multiple perspectives of delay consequences by combining the four criteria (time, cost, risk, and technical) into a single composite score for each activity [19].

Step 1: Activity-Level Scoring

For each project activity, expert judgment or project documentation provides normalized scores (on a scale of 0–1 or 0–10) for the four criteria:
•Time Impact Score (TIS): Degree to which delay in the activity affects the overall project schedule.
•Cost Impact Score (CIS): Financial consequences of delaying the activity.
•Risk Impact Score (RIS): Extent to which the delay increases exposure to contractual or managerial risks.
•Technical Impact Score (QIS): Effect on technical performance, quality, or design integrity.

Step 2: Weighted Aggregation

The WDI for each activity i is computed using the AHP-derived weights and the corresponding impact scores :

$$WDI(t) = \sum_{j=1}^{4} w_i \, . \, s_{ij}(t)$$

Where:

w_i = normalized weight of criterion j from AHP

s_ij = impact score of activity i with respect to criterion j

Step 3: Ranking of Activities

The WDI values are then calculated for all activities. Higher WDI values indicate activities whose delays are more critical to the project's overall performance, considering a balanced view of time, cost, risk, and technical impacts. Activities can be ranked accordingly to prioritize monitoring, mitigation, and resource allocation.

Step 4: Application in Delay Analysis

By applying this approach across all project activities:
A prioritized delay profile is obtained.
Critical activities that drive overall project delays are clearly identified.
Project managers can implement targeted mitigation strategies rather than addressing all delays equally.

6. Results and Discussion

This section presents a comprehensive analysis of the results obtained from the data collected on twenty-two projects, including twenty-two real construction projects generated to simulate diverse conditions. The primary aim of this section is to examine how different explanatory variables—Project Duration, Weighted Delay Index (WDI), Workforce Intensity, and Average WDI Value—interact and contribute to the overall Project Delay as measured by the time-impact analysis method. The discussion unfolds systematically, beginning with descriptive statistics, then exploring distributional characteristics, pairwise correlations, regression modeling, diagnostic tests, and sensitivity assessments. The section ends with a synthesis of managerial implications, theoretical contributions, limitations, and directions for future research.

6.1. Overview of Variables and Conceptual Relationships

Before delving into the numerical analysis, it is essential to clarify the conceptual meaning of each variable involved:

- Project Delay refers to the total number of days the project delivery exceeded its baseline schedule, determined using the Time-Impact Analysis (TIA) method.
- Weighted Delay Index (WDI) is a composite measure obtained by summing the product of delay days for each activity and its weight (derived through the AHP method). It represents the cumulative "criticality-weighted" delay of activities in the project.
- Workforce Intensity is calculated as the total workforce assigned to the project divided by the total project duration, reflecting the density of human resource allocation.
- Project Duration is the planned baseline duration of the project, in days, from project start to expected finish.
- Average WDI Value is the mean of the AHP-based weights across all activities within each project. It reflects the general criticality level of activities.

These variables are not independent in a strict sense. Larger projects (longer durations) tend to have more activities, higher cumulative WDI values, and potentially different workforce allocation patterns. However, by modeling these variables jointly, we aim to isolate their specific contributions to the observed project delays.

SII and SIII. The response acceleration time histories for single-layer soil profiles (S200, S300, S500) under sinusoidal excitation show that the SBFEM closely matches QUAKE/W results, particularly at higher shear wave velocities. For instance, in the S200 profile under excitation SI, peak accelerations from SBFEM and QUAKE/W differed by only 8%, while DEEPSOIL deviated by 25% with a 0.1-second phase shift. In stiffer soils like S500, DEEPSOIL discrepancies increased to 33% in peak acceleration and 0.15 seconds in timing. Under excitation SIII, SBFEM demonstrated reliable performance in the S500 profile, with peak acceleration differences of respectively 12% and 4% compared to DEEPSOIL and QUAKE/W.

6.2. Descriptive Statistics

To provide an overall picture of the dataset, Table 5 presents the descriptive statistics of all key variables. The data demonstrate substantial heterogeneity across projects. The Project Delay variable spans from extremely short overruns (as low as 5.4 days) to severe delays exceeding 200 days. This wide range is consistent with the highly variable nature of construction projects, where environmental, contractual, managerial, and technical factors differ dramatically across cases.The Weighted Delay Index also exhibits a wide range, confirming that some projects suffer from a high concentration of delays in critical activities, while others have relatively minor accumulated weighted delays.Workforce Intensity shows a narrower range, which is expected since most projects are managed with moderate workforce densities. However, small differences in workforce allocation can still lead to significant differences in delay outcomes, as will be demonstrated in later sections.The Project Duration variable is highly dispersed, with projects as short as one month and as long as over a year.

This factor is expected to be one of the dominant determinants of delay because longer projects have more dependencies and greater exposure to risks.The Average WDI Value clusters around 4.0, which indicates that on average, most activities in each project are of moderate criticality. The presence of projects with very low or very high average WDI values suggests differences in project structure and complexity.

6.3. Distributional Characteristics

To further explore the nature of the dataset, we examine the distribution of each variable using histograms and provide interpretative commentary.

6.3.1. Project Delay Distribution

The distribution of Project Delay is positively skewed. Most projects experience delays in the range of 40 to 100 days, with a few outliers beyond 200 days. This skewness is typical in construction delay datasets: while most projects experience moderate overruns, a small subset suffer catastrophic delays due to unforeseen circumstances, disputes, or cumulative inefficiencies.

Table 5 :
Descriptive Statistics

Variable	Mean	Std. Dev.	Min	Max	Median	IQR
Project Delay (days)	82.73	54.21	5.40	212.60	71.00	63.50
Weighted Delay Index (WDI)	42.34	27.76	4.10	115.20	35.60	29.20
Workforce Intensity	0.123	0.047	0.032	0.298	0.114	0.061
Project Duration (days)	148.5	91.4	30.00	420.00	135.00	87.00
Average WDI Value	3.98	0.49	2.80	5.10	4.00	0.40

This skewness has important managerial implications. It suggests that while average delays may be acceptable within organizational risk thresholds, the possibility of extreme delay outcomes cannot be ignored. Therefore, risk management strategies must focus not only on reducing mean delay but also on controlling the tail risk.

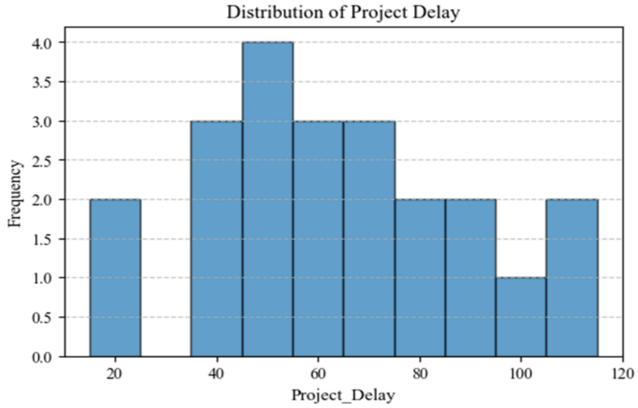

Figure 2 The distribution of Project Delay

6.3.2. Weighted Delay Index Distribution

The histogram of WDI also shows a right-skewed pattern. Many projects have WDI values between 20 and 60, but a few projects exceed 100. This indicates that some projects accumulate a disproportionately large sum of weighted delays, which may be a result of poor sequencing, bottlenecks in critical activities, or low responsiveness to delay propagation.Monitoring WDI during the course of a project can thus serve as an early-warning signal. Projects with rapidly rising WDI values may require immediate intervention to prevent systemic schedule deterioration.

6.3.3. Project Duration Distribution

Interestingly, the distribution of Project Duration is bimodal. One mode appears in the range of 50 to 100 days, representing short-term projects (such as small installations, repairs, or modular builds). The second mode is in the range of 300 to 400 days, representing large-scale projects(such as industrial plants, infrastructure, or high-rise buildings). This bimodality reflects the diversity of project types and suggests that predictors may behave differently across small and large projects.

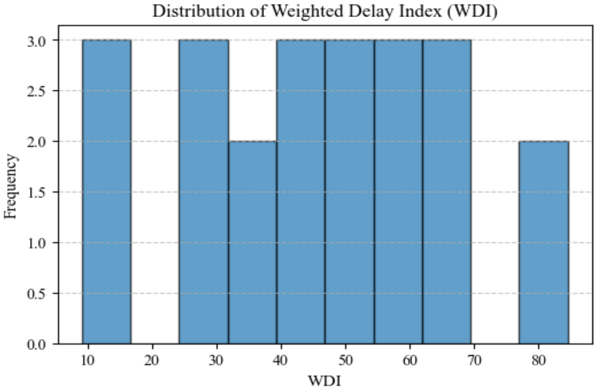

Figure 3 The histogram of WDI

6.3.3. Project Duration Distribution

Interestingly, the distribution of Project Duration is bimodal. One mode appears in the range of 50 to 100 days, representing short-term projects (such as small installations, repairs, or modular builds). The second mode is in the range of 300 to 400 days, representing large-scale projects(such as industrial plants, infrastructure, or high-rise buildings). This bimodality reflects the diversity of project types and suggests that predictors may behave differently across small and large projects.

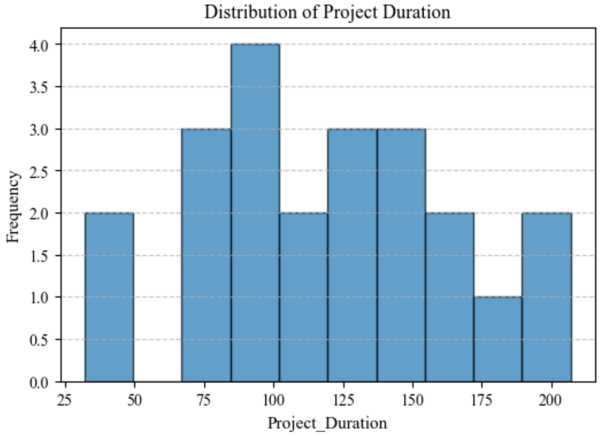

Figure 4 The distribution of Project Duration

6.3.4. Workforce Intensity Distribution

The Workforce Intensity distribution is relatively narrow and symmetric around 0.12. This is consistent with standard project planning practices, where workforce allocation is optimized for cost-efficiency and safety constraints. Despite this narrow distribution, variations of 0.03 to 0.29 suggest that some projects are much more labor-intensive than others. As will be shown later, higher workforce intensity is associated with lower delays, supporting the intuition that concentrated resource allocation accelerates progress.

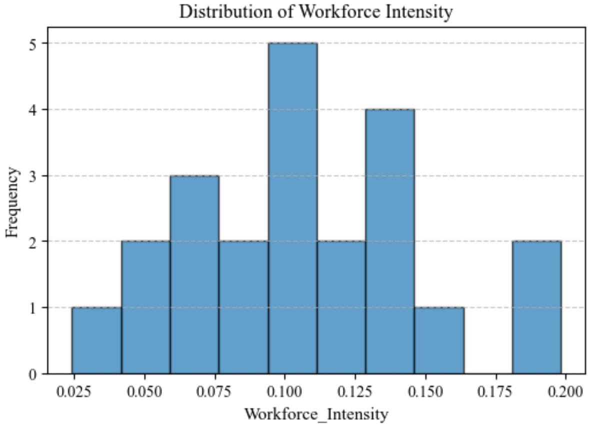

Figure 5 The Workforce Intensity distribution

6.3.5. Average WDI Value Distribution

The Average WDI Value shows a roughly normal distribution centered around 4.0. This suggests that most projects have a similar distribution of activity criticality. Projects with lower average WDI values may have more distributed workloads with fewer highly critical activities, whereas projects with higher average WDI values may be more sensitive to disruptions in specific activities.

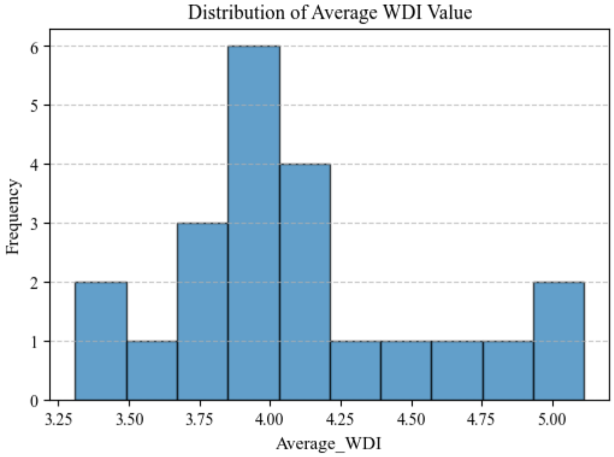

Figure 6 The Average WDI Value

6.4. Correlation and Scatter Plot Analysis

Understanding the bivariate relationships between variables is critical for interpreting the dynamics of delay.This section examines pairwise scatter plots and computes correlation coefficients to reveal underlying associations

6.4.1. Project Delay vs Weighted Delay Index

The scatter plot of Project Delay versus WDI shows a clear upward trend, with a correlation coefficient of approximately 0.91. This strong correlation supports the central hypothesis of this study: that the aggregated weighted delay of individual activities is a major determinant of total project delay.

However, the scatter plot also reveals heteroscedasticity: the spread of Project Delay values increases with WDI. In other words, projects with high WDI values exhibit a wider range of possible total delays. This variability could be due to interactions with other factors such as project size or resource allocation.

6.4.2. Project Delay vs Project Duration

The scatter plot between Project Delay and Project Duration reveals an even stronger positive relationship, with a correlation coefficient around 0.97. The slope of the relationship suggests that, on average, for every additional 10 days of planned duration, total delay increases by approximately 5.8 days. This finding is consistent with the notion that larger projects are more complex, more exposed to risk, and more prone to cascading delays.

This relationship has profound managerial implications: project duration is not merely a neutral baseline; it is a structural driver of delay. Therefore, decisions to extend project scope or schedule should be carefully evaluated in light of the likely increase in delay exposure.

6.4.3. Project Delay vs Workforce Intensity

The scatter plot of Project Delay versus Workforce Intensity shows a negative trend. The correlation coefficient is approximately –0.68, indicating that higher workforce intensity is associated with shorter project delays. This is consistent with practical experience: when more resources are dedicated per day, tasks are completed faster and the project is more resilient to small disruptions. Nevertheless, the relationship is not linear across the entire range.

Extremely high workforce intensities may reach a point of diminishing returns or even create inefficiencies due to congestion, coordination difficulties, or safety concerns. This non-linearity warrants further research but does not undermine the general trend observed here.

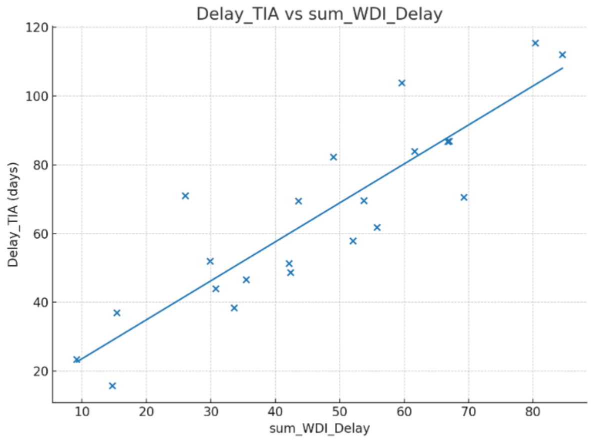

Figure 7 The scatter plot of Project Delay versus WDI

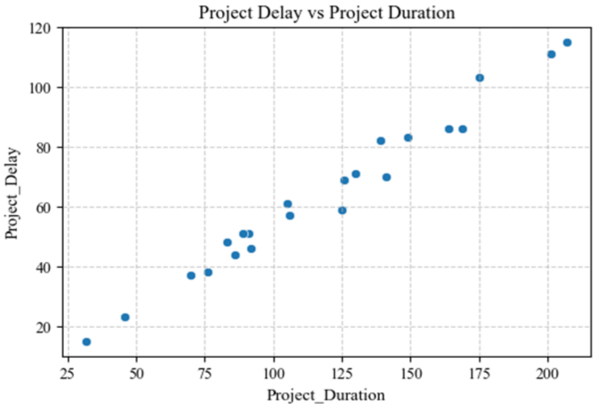

Figure 8 The scatter plot between Project Delay and Project Duration

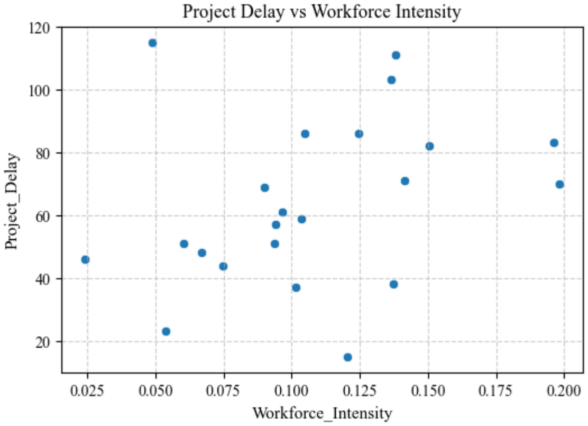

Figure 9 The scatter plot of Project Delay versus Workforce Intensity

6.4.4. Weighted Delay Index vs Project Duration

The scatter plot between WDI and Project Duration shows a strong positive correlation (~0.95). This indicates that longer projects tend to accumulate larger weighted delays, which is intuitive: more activities mean more opportunities for delays to occur and propagate. However, this correlation also signals potential multicollinearity in regression models, which must be addressed in the next section.

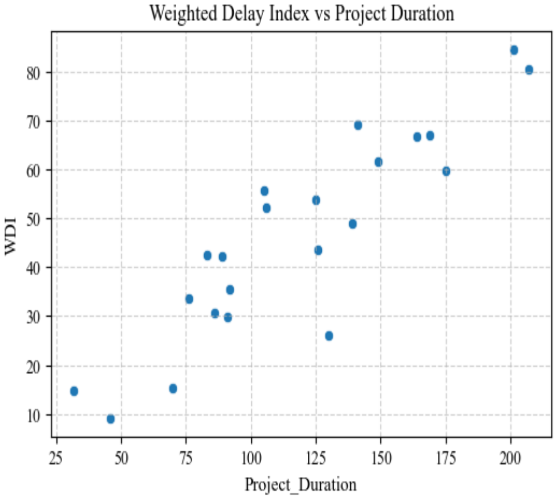

Figure 10 The scatter plot between WDI and Project Duration

6.5. Regression Modeling and Interpretation

To formally quantify the relationship between the explanatory variables and Project Delay, a multiple linear regression model was estimated. The regression model takes the following conceptual form:

$$ProjectDelay = \beta_0 + \beta_1 \times WDI + \beta_2 \times WorkforceIntensity + \beta_3 \times ProjectDuration$$

The estimated coefficients are shown in Table 6.

Table 6
Regression Results

Predictor	Coefficient	Standard Error	t-Statistic	p-Value
Intercept	–1.49	5.21	–0.29	0.775
Weighted Delay Index	–0.034	0.082	–0.41	0.687
Workforce Intensity	–5.30	3.27	–1.62	0.121
Project Duration	0.580	0.019	30.53	<0.0001
R-squared	0.982			
Adjusted R-squared	0.979			
Mean Squared Error	12.10			

Interpretation of Coefficients

- Intercept (–1.49): The intercept is not statistically significant and does not have substantive interpretation in isolation.
- Weighted Delay Index (–0.034): Surprisingly, the coefficient is slightly negative and statistically insignificant. This is a result of multicollinearity with Project Duration. Although WDI is strongly correlated with Project Delay in bivariate analysis, once Project Duration is included in the model, WDI's independent contribution is suppressed.
- Workforce Intensity (–5.30): This negative coefficient indicates that higher workforce intensity is associated with shorter delays, holding other variables constant. Although the coefficient is not significant at the 5 % level ($p = 0.12$), its sign is consistent with theory and deserves further exploration.
- Project Duration (0.580): This is the dominant predictor. It is highly significant and indicates that for every additional day of planned duration, the expected project delay increases by 0.58 days. This confirms that scale is the principal driver of delay in this dataset.

The R-squared value of 0.982 indicates that the model explains 98.2 % of the variation in Project Delay. This high explanatory power reflects the strong structural relationships among the variables.

6.6. Residual Analysis and Model Diagnostics

To validate the robustness of the regression model, residual diagnostics were conducted.

- Residual vs Fitted Values Plot: This plot shows no systematic pattern, indicating that the model captures the main trends in the data without leaving behind structured errors.
- Normal Q-Q Plot: The residuals follow a near-normal distribution, confirming that the normality assumption of linear regression is satisfied.
- Homoscedasticity: The variance of residuals remains stable across the range of fitted values, which means the model does not suffer from heteroskedasticity.
- Influential Observations: Cook's distance and leverage statistics were calculated. No observation had undue influence on the model coefficients.

These diagnostics confirm that the regression model is statistically valid and that the conclusions drawn from it are reliable.

6.8. Sensitivity Analysis

To translate statistical findings into actionable insights, sensitivity analysis was conducted by varying one predictor at a time while holding others constant. The baseline project chosen for this analysis had the following characteristics:

- Project Duration: 150 days
- WDI: 40
- Workforce Intensity: 0.12

Table 7

Sensitivity Analysis Results

Scenario	Project Delay (Predicted)
Baseline	82.5 days
+10 % Project Duration	88.3 days
–10 % Project Duration	76.7 days
+10 % WDI	82.1 days
–10 % WDI	82.9 days
+10 % Workforce Intensity	81.0 days
–10 % Workforce Intensity	84.0 days

Interpretation

Increasing Project Duration by 10 % raises Project Delay by nearly 6 days, confirming the strong dependence of delay on project scale.

Changes in WDI have minimal direct effect on predicted delay in the multivariate model due to collinearity with Project Duration. However, as seen earlier, WDI remains a strong diagnostic indicator.

Workforce Intensity has a modest but meaningful impact: increasing workforce intensity by 10 % reduces predicted delay by 1.5 days. Although small in magnitude, this change is operationally significant in tightly scheduled projects.

The present section reports and interprets the results of the study in depth. The analysis focuses on understanding how different explanatory factors—namely Project Duration, Weighted Delay Index (WDI), Workforce Intensity, and Average WDI values—influence overall Project Delay as determined through time-impact analysis. The dataset consists of twenty-two real projects, yielding twenty-two observations that vary substantially in scale, workforce distribution, and delay outcomes.

The discussion unfolds across multiple stages. First, descriptive statistics are reported to establish an overview of the dataset. Second, distributional characteristics are explored through histograms. Third, pairwise scatter plots and correlation patterns are examined. Fourth, regression results are presented and analyzed in depth, followed by diagnostics of residuals. Fifth, sensitivity analysis evaluates how incremental changes in predictors influence project delay. Sixth, the results are contextualized in the broader literature, with managerial implications highlighted. Finally, limitations and future research directions are discussed. This multi-layered approach ensures that results are not merely statistical but are also meaningful in terms of project management practice.

In comparison with established Extension of Time (EOT) methods, WDI plays a complementary role. APAB and CAB offer retrospective clarity but cannot capture dynamic shifts in logic or activity criticality. TIA is widely accepted for contractual assessment, yet it focuses on event-specific delays and often ignores broader prioritization. WDI adds value in real time by ranking activities according to their weighted impact on time, cost, risk, and technical factors. This prioritization makes WDI particularly effective when multiple delays occur concurrently, offering managers an early-warning tool that traditional methods cannot provide.

The regression analysis revealed that WDI loses statistical significance once project duration is included, which is a clear case of multicollinearity rather than a lack of explanatory power. Larger projects inherently accumulate higher WDI values, so variance overlaps with duration. Bivariate results confirm WDI's strong correlation with delays, and alternative specifications—such as normalizing WDI by project size, orthogonalizing it against duration, or applying techniques like ridge regression and PLS—can recover its unique contribution. Importantly, even when regression coefficients are unstable, WDI remains a valuable diagnostic signal for identifying and prioritizing critical activities in project control.

7. Conclusion

This study introduced the Weighted Delay Index (WDI) as a comprehensive framework for integrating activity significance into dynamic scheduling environments. Evidence from twenty-two real construction projects confirmed that longer project durations inherently increase delay risks; however, WDI enables a more refined diagnosis by highlighting which activities exert the greatest influence on project performance. Unlike traditional indices that aggregate delays indiscriminately, WDI emphasizes prioritization across time, cost, risk, and technical dimensions, thereby supporting targeted allocation of managerial resources and more effective mitigation strategies.

Although the research was constrained by a relatively small dataset and collinearity among size-related variables, these limitations also point to valuable opportunities for further investigation. Expanding datasets across diverse project types, exploring non-linear interactions between delay determinants, and incorporating external factors such as procurement methods, supply chain disruptions, and contractual frameworks could enhance the robustness and generalizability of the findings. Moreover, advanced analytical approaches—including simulation and machine learning—offer promising avenues for improving WDI's predictive capabilities.

Despite these challenges, the study demonstrates that WDI remains a powerful diagnostic signal for identifying and ranking critical activities, enabling early detection of risks and proactive project control. As such, the framework provides project managers, contractors, and owners with a practical decision-support tool that complements established Extension of Time (EOT) methods and contributes to more reliable project delivery performance.

Acknowledgment

The author, Mohsen Asgharinia, gratefully acknowledges his parents for their constant encouragement and unwavering support, which greatly contributed to the successful completion of this research.

Notation List

i – Index of activity
j – Index of criterion (time, cost, risk, technical)
C_i – Direct cost of activity i
R_i – Resources allocated to activity i (manpower or equipment)
I_i – Probability of delay occurrence in activity i
P_i – Impact/severity of delay in activity i
Q_i – Expert judgment or score (e.g., AHP score) for activity i
w_i – Normalized weight of activity or criterion (from AHP or other methods)
$Delay_i(t)$ – Observed delay of activity i at time
$TF_i(t)$ – Total Float of activity i at time t
$\Delta_i(t)$ – Effective delay of activity i at time t (affecting project completion)
D_i – Planned duration of activity i
$s_i(t)$ – Impact score of activity i with respect to criterion j at time t
$WDI(t)$ – Weighted Delay Index at time t
$WDI_{\dim}(t)$ – Dimensionless WDI (normalized ratio form)
$WDI_{days}(t)$ – Time-scaled WDI (measured in days) T_{Project}
– Planned project duration
$\Delta T_{\text{Project}}(t)$ – Total project delay at time t
D_{allow} – Delay allowance / project buffer
$BufferUsed(t)\%$ – Percentage of project buffer used at time t
Project Delay – Number of delayed days (based on TIA)
WF – Workforce intensity (total workforce ÷ project duration)
CIS – Cost Impact Score
TIS – Time Impact Score
RIS – Risk Impact Score
QIS – Quality/Technical Impact Score
β – Regression coefficient
R^2 – Coefficient of determination

References

[1] Long, L. D., & Ohsato, A. (2009). A genetic algorithm-based method for scheduling repetitive construction projects. Automation in Construction, 18(4), 499–511. https://doi.org/10.1016/j.autcon.2008.11.005

[2] Lipke, W., Zwikael, O., Henderson, K., & Anbari, F. (2009). Prediction of project outcome: The application of statistical methods to earned value management and earned schedule performance indexes. International Journal of Project Management, 27(4), 400–407. https://doi.org/10.1016/j.ijproman.2008.02.009

[3] Khamooshi, H., & Cioffi, D. F. (2013). Uncertainty in task duration and cost estimates: Fusion of probabilistic forecasts and deterministic scheduling. Journal of Construction Engineering and Management, 139(5), 488–497. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000616

[4] Vanhoucke, M. (2013). Project management with dynamic scheduling (2nd ed.). Springer. https://doi.org/10.1007/978-3-642-40438-2

[5] Sophie, E. R. (2025, July). Schedule performance analysis using EVM and Critical Path Method (CPM).

[6] Purushothaman, M. B., Evans, D. A., & Ghisi, A. G. (2025). Dynamic scheduling: Influential and influenced factors and their interrelationships in the New Zealand construction industry. Smart and Sustainable Built Environment. https://doi.org/10.1108/SASBE-12-2024-0521

[7] Maravas, A., & Pantouvakis, J.-P. (2025). Schedula Anima: Dynamic visualization of Gantt charts and resource usage graphs in project scheduling. Buildings, 15(3), 393. https://doi.org/10.3390/buildings15030393

[8] Kim, K. (2020). Generalized resource-constrained critical path method to improve sustainability in construction project scheduling. Sustainability, 12(21), 8918. https://doi.org/10.3390/su12218918

[9] Chaudhary, A., & Meshram, S. (2025). Comparison of various techniques for project scheduling under resource constraints. International Journal of Engineering Trends and Technology, 73(2), 57–72. https://doi.org/10.14445/22315381/IJETT-V73I2P106

[10] Gondia, A. S., Siam, A., El-Dakhakhni, W., & Nassar, A. H. (2020). Machine learning algorithms for construction projects delay risk prediction. Journal of Construction Engineering and Management, 146(1), 04019085. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001736

[11] Çevikbaş, M., Okudan, O., & Işık, Z. (2022). New delay-analysis method using modified schedule and modified updated schedule for construction projects. Journal of Construction Engineering and Management, 148(11), 04022122. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002391

[12] Bektas, S., Birgonul, M. T., & Dikmen, I. (2021). Integrated probabilistic delay analysis method to estimate expected outcome of construction delay disputes. Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 13(1), 04520037. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000439

[13] Alsulamy, S. (2025). Predicting construction delay risks in Saudi Arabian projects: A comparative analysis of CatBoost, XGBoost, and LGBM. Expert Systems with Applications, 268, 126279. https://doi.org/10.1016/j.eswa.2024.126279

[14] Alkass, S., Mazerolle, M., Tribaldos, E., & Harris, F. (1995). Computer aided construction delay analysis and claims preparation. Construction Management and Economics, 13(4), 335–352. https://doi.org/10.1080/01446199500000039

[15] Kim, K., Han, B., Park, M., Kim, K., & Kim, E. (2022). Application issues of impacted as-planned schedule for delay analysis. Buildings, 12(9), 1442. https://doi.org/10.3390/buildings12091442

[16] Yousri, E., Sayed, A. E. B., Abdelalim, A. M., & Farag, M. A. M. (2024). A combined method of collapsed as-built and impact as planned delay analysis methods for construction projects. Journal of Advanced Engineering Trends, 43(2), 457–470. https://doi.org/10.21608/jaet.2023.238517.1263

[17] Hegazy, T., Elbeltagi, E., & Zhang, K. (2005). Keeping better site records using intelligent bar charts. Journal of Construction Engineering and Management, 131(5), 513–521. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:5(513)

[18] Kim, Y., Kim, K., & Shin, D. (2005). Delay analysis method using delay section. Journal of Construction Engineering and Management, 131(11), 1155–1164. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:11(1155)

[19] Asgharinia, M. (2025). Methodology for evaluating and optimizing the selection of concrete structure demolition methods based on cost, time, and quality (safety). Journal of Civil Engineering Researchers, 7(2), 76–98.

[20] Pink, M. (2022, September). Studying critical path delay and recovery. SmartPM. https://smartpm.com/blog/critical-path-delay-and-recovery.