

From Schedule Monitoring to Operational Intelligence: Workforce Bottleneck Analytics in Construction

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Abstract

Construction workforce allocation represents a critical operational variable in construction logistics management, directly influencing project flow efficiency, schedule reliability, and overall performance. In complex construction systems, bottlenecks emerge as dynamic constraints within interconnected activity networks, disrupting labor flow and amplifying delay propagation. Despite its operational importance, bottleneck identification in construction scheduling remains largely heuristic and experience-driven. This study proposes a workforce bottleneck analytics framework derived from operational combinatorial modeling to quantitatively capture interactions among activity sequencing, workforce allocation, and schedule dynamics. The analytical framework translates construction scheduling into measurable operational patterns reflecting workforce allocation behavior, task interdependency, and schedule deterioration mechanisms. Multiple workforce allocation scenarios are subsequently generated and analyzed to identify recurring resource-deficient activities associated with unfavorable scheduling outcomes. The proposed framework is validated through a real-world case study of a three-story urban building project in Pekanbaru, Indonesia. Results demonstrate that the integration of analytical modeling and workforce bottleneck occurrence analysis enables systematic, data-driven bottleneck identification and reveals recurring operational patterns embedded within construction scheduling systems. The findings indicate that schedule degradation is strongly influenced by recurring workforce allocation deficiencies rather than solely by critical path logic. More importantly, the study provides empirical evidence that construction scheduling contains observable and repeatable operational structures that can be systematically extracted from project data and transformed into operational knowledge. The approach transforms conventional schedule tracking into an operational intelligence framework that supports proactive workforce management and provides a foundation for future artificial intelligence and advanced analytics applications in construction project control.

Keywords

Construction scheduling; workforce allocation; workforce bottleneck analytics; operational intelligence; recurring operational patterns; project performance.

1. Introduction

Construction projects operate as complex production systems in which project performance is governed by the interaction of activities, resources, and operational constraints (Singh, 2015; Kurniawati and Wisena, 2023; Fitria et al., 2025; Althoey et al., 2024; Ibrahim et al., 2025). Among the various resources involved in project execution, workforce allocation plays a particularly important role because it directly influences productivity, workflow continuity, schedule reliability, and overall project performance (Althoey et al., 2024; Ibrahim et al., 2025). Variations in workforce allocation may alter activity durations, disrupt workflow sequences, and ultimately affect project completion time. Consequently, understanding the relationship between workforce allocation and schedule behavior has become increasingly important in modern construction management.

Despite significant advances in scheduling techniques, construction project control remains largely centered on schedule monitoring and progress reporting (Singh, 2015; Kurniawati and Wisena, 2023). Conventional approaches such as Critical Path Method (CPM), Earned Value Management (EVM), and progress-based monitoring systems are effective in measuring project status and identifying schedule deviations. However, these approaches primarily function as retrospective monitoring tools, providing information regarding what has occurred rather than explaining why performance deterioration occurs. As a result, project managers often rely on experience and subjective judgment to interpret operational conditions and identify the underlying causes of project delays (Singh, 2015; Karimi et al., 2024).

One of the most critical operational issues affecting schedule performance is the emergence of workforce bottlenecks. Workforce bottlenecks occur when insufficient labor allocation within specific activities disrupts workflow continuity and propagates delays throughout the project network. In practice, bottleneck identification is frequently performed through managerial intuition and field experience rather than systematic analytical procedures (Karimi et al., 2024; Panahi et al., 2023; Thekinen et al., 2023). Consequently, workforce-related operational knowledge often remains implicit, making it difficult to formalize, replicate, or integrate into data-driven decision-support systems.

This limitation becomes increasingly important as the construction industry moves toward digital project management environments characterized by growing volumes of operational data. Recent developments in artificial intelligence, digital twins, big data analytics, and intelligent project control systems have significantly expanded the capability of project monitoring and decision-support technologies (Ibrahim et al., 2025; Chen et al., 2025; Gill et al., 2024; Tolba et al., 2025; Mohammadi et al., 2025; Memon et al., 2025; Soofastaei, 2025). However, relatively limited attention has been devoted to understanding whether operational behaviors embedded within scheduling data exhibit recurring patterns that can be systematically extracted and transformed into actionable knowledge. In other words, an important question remains unanswered: can construction scheduling data reveal operational intelligence beyond conventional schedule monitoring?

The concept of operational intelligence suggests that project data should not merely be used to report project status but should also be capable of revealing operational mechanisms responsible for project performance (Mohammadi et al., 2025). From this perspective, workforce allocation behavior represents a potentially valuable source of operational intelligence because workforce decisions directly influence activity durations, critical path formations, and project completion times. If recurring workforce-related operational patterns can be identified from scheduling outcomes, these patterns may provide a foundation for developing more proactive and intelligence-driven project control systems.

Recent studies have demonstrated the growing potential of artificial intelligence and data analytics in construction scheduling, including critical path generation, schedule optimization, productivity monitoring, risk assessment, and project performance prediction (Ghasemi and Keihani, 2025; Le and Jeong, 2020; Hatami et al., 2022; Jha et al., 2022; Pourrahimian et al., 2024; Guo, 2025; Roy et al., 2025; Unegbu and Yawas, 2025; Soofastaei, 2025). Several studies have explored machine learning applications for schedule forecasting (Ghasemi and Keihani, 2025; Jha et al., 2022), productivity control (Pourrahimian et al., 2024), critical path development (Le and Jeong, 2020), and intelligent scheduling optimization (Guo, 2025; Roy et al., 2025). Nevertheless, most existing studies focus on predictive performance and optimization capabilities, while relatively few investigate whether recurring operational patterns can first be systematically extracted from scheduling behavior itself. As a result, the analytical foundation linking construction scheduling data to operational intelligence remains insufficiently explored.

To address this gap, this study proposes a mathematical workforce bottleneck analytics framework based on dynamic workforce allocation simulations and bottleneck occurrence analysis. The framework generates multiple workforce allocation scenarios, evaluates the resulting scheduling outcomes, and identifies resource-deficient activities that repeatedly emerge under unfavorable scheduling conditions. By analyzing the recurrence of workforce deficiencies across multiple scheduling realizations, the study seeks to determine whether identifiable operational patterns exist within construction scheduling systems and whether these patterns can be transformed into operational knowledge.

The study contributes to the existing body of knowledge in three ways. First, it introduces a mathematical framework for identifying workforce bottlenecks through recurring resource-deficiency patterns rather than relying solely on deterministic critical path logic. Second, it demonstrates that workforce allocation behavior contains observable and measurable operational structures that can be systematically extracted from scheduling data. Third, it provides an initial analytical foundation for operational intelligence in construction management by showing that recurring operational patterns exist within project scheduling systems and may serve as a basis for future applications involving artificial intelligence, machine learning, digital twins, and intelligent decision-support technologies (Chen et al., 2025; Gill et al., 2024; Ghasemi and Keihani, 2025; Le and Jeong, 2020; Hatami et al., 2022; Jha et al., 2022; Pourrahimian et al., 2024; Guo, 2025; Roy et al., 2025; Unegbu and Yawas, 2025; Tolba et al., 2025; Mohammadi et al., 2025; Memon et al., 2025; Soofastaei, 2025).

The remainder of this paper is organized as follows. Section 2 describes the proposed methodology and operational intelligence framework. Section 3 presents the simulation results and bottleneck occurrence analysis. Section 4 discusses the implications of the findings for operational intelligence in construction scheduling. Finally, Section 5 concludes the study and outlines directions for future research.

2. Method

To investigate the feasibility of operational intelligence in construction scheduling, a mathematical simulation framework was developed to systematically explore the relationship between workforce allocation, scheduling behavior, and project performance. The framework was designed based on the premise that operational decisions made during project execution generate observable patterns that can be represented analytically and extracted from scheduling data. Consequently, the proposed methodology seeks to transform workforce allocation behavior into measurable operational indicators capable of supporting future intelligence-driven decision-making systems.

This study adopted a simulation-based operational analytics approach consisting of three primary phases: (1) dynamic scheduling formulation, (2) workforce allocation scenario generation, and (3) bottleneck occurrence analytics. Figure 1 presents the conceptual foundation of the proposed operational intelligence framework, while Figure 2 illustrates the detailed research workflow and implementation procedure.

2.1 Operational Intelligence Framework

Figure 1 illustrates the conceptual framework developed in this study. The process begins with a baseline construction schedule represented as an interconnected activity network. Since activity durations are highly dependent on workforce allocation, resource distribution is incorporated into the scheduling process to reflect actual operational conditions. Variations in workforce allocation generate variations in activity durations, which subsequently produce alternative critical path formations and project durations. Unlike conventional scheduling approaches that generate a single deterministic critical path, the proposed framework produces a population of scheduling outcomes representing different operational conditions within the project system. Each workforce allocation configuration generates a unique scheduling realization characterized by a specific critical path and overall project duration. The resulting scheduling scenarios are subsequently compiled into a scenario database that serves as the foundation for identifying recurring operational patterns.

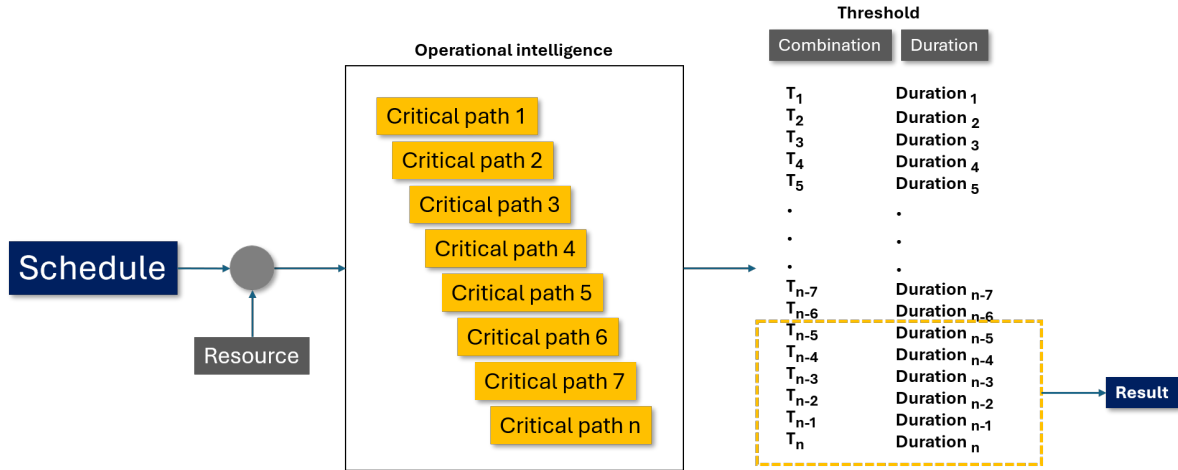


Figure 1. Operation intelligence mathematical framework

The final stage of the framework involves workforce bottleneck analytics. By comparing workforce allocation behavior across multiple scheduling scenarios, activities repeatedly associated with poor-performing outcomes can be systematically identified. These recurring patterns provide quantitative evidence of operational constraints and form the basis for extracting operational intelligence from project scheduling data.

2.2 Dynamic Critical Path Network Formulation

To demonstrate the applicability of the proposed framework, a three-story building construction project was selected as the case study. The analysis was limited to structural works, architectural works, mechanical works, and electrical works, representing the primary operational components governing project execution. The project was decomposed into WBS Level 3 activities, and a dynamic critical path network was subsequently formulated to represent the logical relationships among activities. Unlike conventional critical path scheduling, where activity durations are predefined and remain fixed throughout the analysis, the proposed framework treats activity duration as a dynamic variable influenced by workforce allocation. Several operational parameters were identified for each activity, including WBS definition, predecessor relationships, work quantities, productivity coefficients expressed in man-hours (OH), workforce allocation, and units of measurement. The predecessor relationships establish the scheduling topology, while work quantities and productivity coefficients define workload requirements. Workforce allocation serves as the primary decision variable governing activity duration. Based on these parameters, activity durations are generated dynamically through the interaction between workload, productivity, and allocated workforce resources. Consequently, different workforce allocation configurations produce different scheduling outcomes and alternative critical path formations. This dynamic scheduling mechanism forms the analytical foundation of the proposed operational intelligence framework.

2.3 Workforce Allocation Scenario Generation

The dynamic critical path network enables the generation of multiple scheduling outcomes through variations in workforce allocation. To explore the operational behavior of the scheduling system, seven independent simulation attempts were performed. Each attempt generated a population of workforce allocation scenarios and their corresponding project durations. The purpose of conducting multiple attempts was to capture a wider range of feasible workforce allocation conditions and increase the diversity of scheduling outcomes. As a result, the simulation process produced a large set of alternative critical paths and project durations representing different operational states of the project system. For each attempt, the generated scheduling scenarios were ranked according to project duration. Since the objective of the study was to investigate operational conditions associated with schedule degradation, attention was focused on the worst-performing scheduling outcomes. Therefore, the seven longest project durations from each simulation attempt were selected for further analysis.

2.4 Workforce Bottleneck Occurrence Analytics

Following the identification of the worst-performing scheduling scenarios, workforce utilization data were extracted for each project activity. The utilization values were organized according to activity identifiers to evaluate workforce allocation behavior across multiple scheduling outcomes. To isolate potential operational bottlenecks, a resource-deficient activity criterion was introduced. Resource-deficient activities are defined as activities exhibiting workforce utilization values equal to zero or one,

indicating that the activity received either no workforce allocation or only a minimal workforce allocation under a particular scheduling scenario. Such conditions represent severe workforce shortages that may significantly reduce productivity and contribute to project delay formation. The identified resource-deficient activities from all simulation attempts were subsequently aggregated into a unified dataset. The occurrence frequency of each activity was then calculated to determine how frequently it appeared under unfavorable scheduling conditions. Activities exhibiting higher occurrence frequencies were interpreted as dominant workforce bottlenecks because they repeatedly emerged within poor-performing scheduling scenarios.

Finally, the resulting occurrence frequencies were ranked and visualized to produce a workforce bottleneck profile. This profile constitutes the primary analytical output of the proposed framework and serves as the basis for identifying workforce-sensitive activities that contribute most significantly to schedule degradation. More importantly, the resulting bottleneck patterns provide empirical evidence that operational behaviors within construction scheduling can be systematically represented, quantified, and extracted through analytical procedures, thereby supporting the development of future operational intelligence systems.

3. Result

The implementation of the proposed operational intelligence framework began with the development of a dynamic critical path network representing the operational structure of the case study project. The selected project consists of twenty-eight WBS Level 3 activities covering structural, architectural, mechanical, and electrical works. Each activity was characterized by its predecessor relationships, workload quantity, productivity coefficient expressed in man-hours (OH), and measurement unit. These parameters collectively define the operational behavior of the scheduling system and serve as the primary inputs for the workforce allocation simulations.

Unlike conventional scheduling approaches that rely on predefined activity durations, the proposed framework utilizes workload and productivity information to dynamically generate activity durations under varying workforce allocation conditions. Consequently, the activity network forms the foundation for generating multiple scheduling scenarios and alternative critical path realizations throughout the simulation process.

Table 1 presents the complete project activity dataset used in this study. The table summarizes the WBS Level 3 activities, activity identifiers, predecessor relationships, productivity coefficients, work quantities, and units of measurement that constitute the analytical basis of the dynamic scheduling model.

Table 1 Case activity dataset and scheduling parameters

No	WBS Level 3	ID	Predecessor	Man-Hour (OH)	Qty	Units
1	Site Clearing	A	-	0,015	300	m ²
2	Site Layout and Staking	B	-	0,2	24	point
3	Second Floor Ceramic Finishing	C	A,B	0,45	145	m ³
4	Third Floor Painting	D	C	2,2	108	m ³
5	Foundation Excavation	E	D	2,6	68	m ³
6	First Floor Column Construction	F	E	3	52	m ³
7	First Floor Lean Concrete Work	G	E	1	32	m ³
8	Second Floor Mechanical and Electrical Installation	H	F	3,4	126	m ³
9	Third Floor Wall Construction	I	H	3	48	m ³
10	Ground Beam (Sloof) Construction	J	H	0,35	620	m ²
11	Second Floor Column Construction	K	H	0,8	120	point
12	First Floor Wall Construction	L	I	3,4	118	m ³
13	First Floor Mechanical and Electrical Installation	M	K	0,22	216	m ²
14	First Floor Ceramic Finishing	N	G	0,28	216	m ²
15	Second Floor Ceiling Installation	O	L	3	44	m ³

No	WBS Level 3	ID	Predecessor	Man-Hour (OH)	Qty	Units
16	Third Floor Ceramic Finishing	P	L	0,35	580	m ²
17	Third Floor Ceiling Installation	Q	J,M,N	0,12	1,24	m ²
18	Second Floor Painting	R	O	3,2	96	m ³
19	Foundation Construction	S	H	0,28	216	m ²
20	Second Floor Beam and Slab Construction	T	L	0,8	110	point
21	Third Floor Column Construction	U	R	0,25	260	m ²
22	Second Floor Wall Construction	V	T	0,22	216	m ²
23	Third Floor Beam and Slab Construction	W	R	0,35	540	m ²
24	Roof Beam Construction	X	U	0,8	100	point
25	Pengecatan lantai 2	Y	P,V,S	0,12	1,16	m ²
26	Pekerjaan keramik lantai 3	Z	L	0,28	216	m ²
27	Plafond lantai 3	AA	X	0,22	216	m ²
28	Pengecatan lantai 3	BB	AA,W,Z	0,12	1,08	m ²

Table 1 presents the complete activity dataset used to construct the dynamic critical path network model. The project consists of twenty-eight WBS Level 3 activities spanning structural, architectural, mechanical, and electrical works. Each activity is represented by a unique identifier and linked through predecessor relationships that define the logical sequence of project execution. The dataset also includes productivity coefficients expressed in man-hours (OH), work quantities, and measurement units, which collectively determine the workload characteristics of each activity.

The activity network demonstrates a high degree of interdependency among project operations. Structural activities such as foundation construction, columns, beams, slabs, and roof structures form the primary execution backbone of the project, while architectural and mechanical-electrical activities are progressively introduced following the completion of preceding structural works. This dependency structure creates multiple pathways through which delays may propagate across the project network, making workforce allocation an important determinant of schedule performance.

A notable characteristic of the dataset is that activity durations are not explicitly predefined. Instead, durations are generated dynamically based on the interaction between work quantities, productivity coefficients, and workforce allocation levels. As a result, any variation in workforce distribution may alter activity durations, modify the resulting critical path configuration, and ultimately influence overall project duration. This dynamic behavior enables the scheduling model to produce multiple alternative scheduling outcomes from the same project network.

Consequently, the activity dataset presented in Table 1 serves not only as a scheduling input but also as the analytical foundation for exploring workforce allocation behavior, identifying recurring resource deficiencies, and extracting operational intelligence from the resulting scheduling scenarios. The dynamic scheduling outcomes generated from this dataset are presented and analyzed in the subsequent sections.

Following the development of the dynamic critical path network, workforce allocation simulations were performed to explore the influence of resource distribution on project schedule performance. Since activity durations are generated dynamically from workload characteristics and workforce allocation levels, different workforce configurations produce different project durations and alternative critical path realizations. Consequently, the same project network may exhibit substantially different scheduling outcomes depending on how available labor resources are distributed among activities.

To capture this behavior, multiple workforce allocation combinations were generated and evaluated through the proposed simulation framework. Each combination represents a unique resource allocation scenario characterized by a specific distribution of workforce resources across project activities. For every scenario, activity durations were recalculated, the corresponding critical path was determined, and the resulting overall project duration was recorded.

Table 2 presents a sample of the scheduling outcomes generated from the simulation process. Each record consists of a workforce allocation combination and its corresponding project duration. The results demonstrate significant variability in project completion times across different resource allocation configurations, with durations ranging from the shortest-performing scenarios to substantially longer schedules. This variation indicates that workforce allocation exerts a considerable influence on project performance and provides evidence that operational behavior within the scheduling system is highly sensitive to resource distribution decisions.

The generated scenario database constitutes the foundation for the subsequent bottleneck analysis. By examining scheduling outcomes associated with unfavorable project durations, recurring workforce allocation patterns can be identified and used to reveal operational constraints that contribute most significantly to schedule degradation.

Table 2. Workforce allocation scenarios and resulting project durations

Scenario	1	2	3	.....	26	27	28	Duration
T5	9	21	11	.....	20	14	19	132,8462
T1	13	8	7	.....	19	21	12	144,7553
T16	19	21	12	.....	19	14	15	147,5852
T12	8	15	12	.....	20	8	20	154,5933
T21	12	15	10	.....	13	18	21	154,6579
T8	18	16	8	.....	9	8	20	154,7433
T13	12	13	19	.....	14	11	20	155,1767
T20	8	15	12	.....	20	12	21	157,2853
T10	21	15	14	.....	12	19	12	159,0187
T11	12	10	8	.....	15	11	17	162,2224
T9	8	17	17	.....	15	20	17	162,7017
T19	15	16	7	.....	16	14	15	164,7249
T17	19	11	8	.....	15	19	19	164,8595
T3	9	10	15	.....	11	13	20	165,469
T7	7	8	9	.....	16	12	15	171,1854
T14	13	8	21	.....	18	19	10	174,6312
T24	19	21	17	.....	20	7	19	176,7222
T1	17	9	11	.....	7	13	9	178,8251
T22	18	12	19	.....	9	15	11	178,9127
T4	14	20	7	.....	17	14	10	180,2928
T9	17	16	16	.....	19	11	16	181,5248
T18	8	9	14	.....	13	20	15	184,7153
T24	15	12	21	.....	8	7	19	186,1378
T4	17	15	8	.....	16	14	19	189,3856
T16	10	19	13	.....	16	15	21	189,6369
T13	12	20	15	.....	21	21	11	190,7829
T5	18	14	15	.....	15	18	10	191,328
T20	10	7	14	.....	14	15	7	191,434
T6	14	14	20	.....	20	7	15	191,9663
T10	20	17	21	.....	17	10	15	196,4644
T7	19	13	16	.....	21	8	13	196,4792
T17	16	12	19	.....	20	21	21	199,2989

Scenario	1	2	3	.....	26	27	28	Duration
T15	13	8	10	.....	9	20	7	199,7927
T15	10	13	11	.....	19	21	20	200,6666
T23	11	7	20	.....	15	8	13	203,1055
T11	13	17	8	.....	16	14	7	203,3213
T18	8	9	16	.....	7	16	12	205,0392
T19	12	21	13	.....	10	10	11	205,7011
T14	20	16	13	.....	18	21	16	205,888
T21	13	18	14	.....	18	20	13	208,2966
T12	11	11	21	.....	14	11	11	208,5084
T6	18	19	15	.....	12	16	9	208,5193
T23	11	12	20	.....	10	19	16	211,2935
T8	20	7	21	.....	15	7	10	216,8045
T2	21	15	7	.....	7	12	19	217,3003
T22	8	12	10	.....	18	13	7	229,5067
T2	9	21	11	.....	14	18	18	232,6917
T3	9	12	15	.....	18	17	19	245,5041

Table 2 presents the scheduling outcomes generated from the workforce allocation simulation process. Each row represents a unique workforce allocation configuration, where the numerical values correspond to the allocated workforce utilization assigned to individual project activities. The resulting project duration is subsequently calculated through the dynamic critical path network model, allowing the influence of workforce allocation decisions on overall schedule performance to be observed.

The results demonstrate considerable variation in project duration across different workforce allocation configurations. Although all scenarios were generated from the same project network and operational dataset, the resulting durations range from approximately 132.85 days to 245.50 days. This variation confirms that workforce allocation is a significant determinant of schedule performance and that different resource distribution strategies can produce substantially different project outcomes.

An important observation from Table 2 is that identical project structures do not necessarily lead to identical schedule durations. Variations in workforce allocation alter activity durations, resulting in alternative critical path formations and different project completion times. This behavior supports the fundamental premise of the proposed framework that operational conditions within construction projects are dynamic and highly dependent on resource allocation decisions.

To investigate the operational mechanisms associated with schedule deterioration, the analysis focused on the worst-performing scheduling outcomes. Therefore, the seven scenarios exhibiting the longest project durations, highlighted in Table 2, were selected for further evaluation. These scenarios represent workforce allocation conditions associated with the highest levels of schedule degradation and are therefore expected to contain the strongest indicators of workforce bottlenecks.

Rather than examining all generated scenarios equally, concentrating on the longest-duration schedules enables the analysis to isolate operational conditions that contribute most significantly to project delay formation. The selected scenarios subsequently serve as the basis for workforce utilization assessment and resource-deficient activity identification. By comparing workforce allocation patterns across these adverse scheduling outcomes, recurring workforce deficiencies can be systematically extracted and transformed into a bottleneck occurrence profile, which forms the primary analytical output of the proposed operational intelligence framework.

To further investigate the workforce allocation characteristics associated with poor scheduling performance, the same simulation procedure was repeated across seven independent attempts using different workforce allocation combinations. Each attempt generated a distinct dataset containing alternative workforce allocation scenarios and their corresponding project durations. Following the procedure described in the previous section, the scheduling outcomes within each dataset were ranked according to project duration, and the seven longest-duration scenarios were selected for further evaluation.

The workforce utilization values associated with the selected scenarios were subsequently extracted and visualized to examine resource allocation behavior across project activities. Figures 2–8 present the resulting workforce utilization distributions for each simulation attempt. These charts provide a comparative representation of workforce allocation patterns under adverse scheduling conditions and serve as the basis for identifying recurring resource-deficient activities associated with project delay formation.

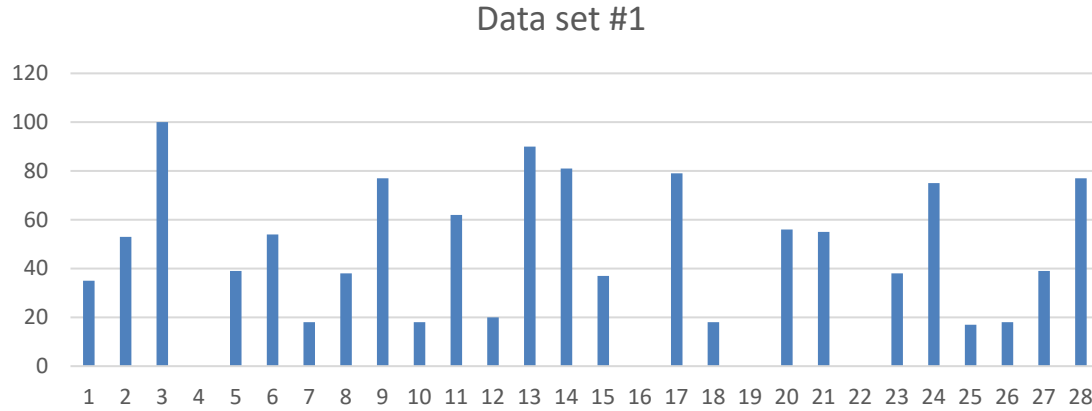


Figure 2. Resource Allocation Distribution Extracted from the Longest-Duration Scheduling Scenarios (Data Set #1)

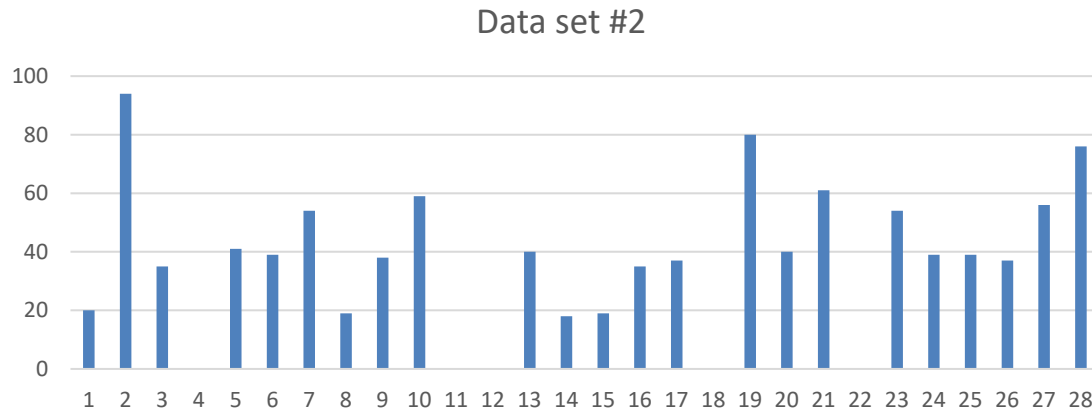


Figure 3. Resource Allocation Distribution Extracted from the Longest-Duration Scheduling Scenarios (Data Set #2)

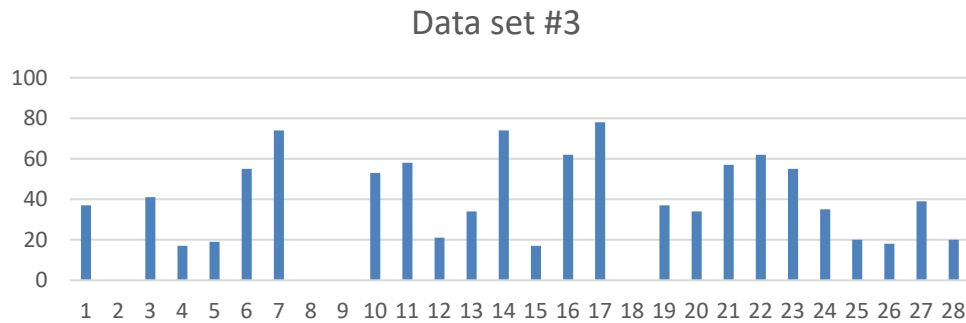


Figure 4. Resource Allocation Distribution Extracted from the Longest-Duration Scheduling Scenarios (Data Set #3)

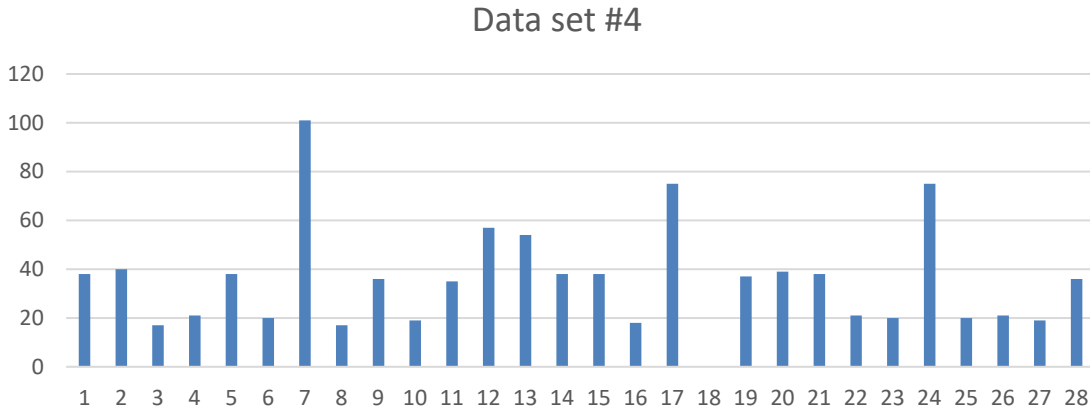


Figure 5. Resource Allocation Distribution Extracted from the Longest-Duration Scheduling Scenarios (Data Set #4)

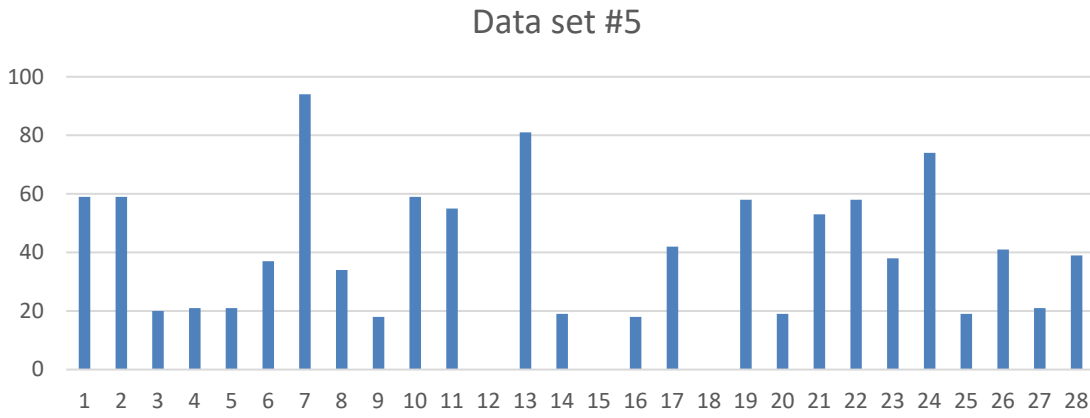


Figure 6. Resource Allocation Distribution Extracted from the Longest-Duration Scheduling Scenarios (Data Set #5)

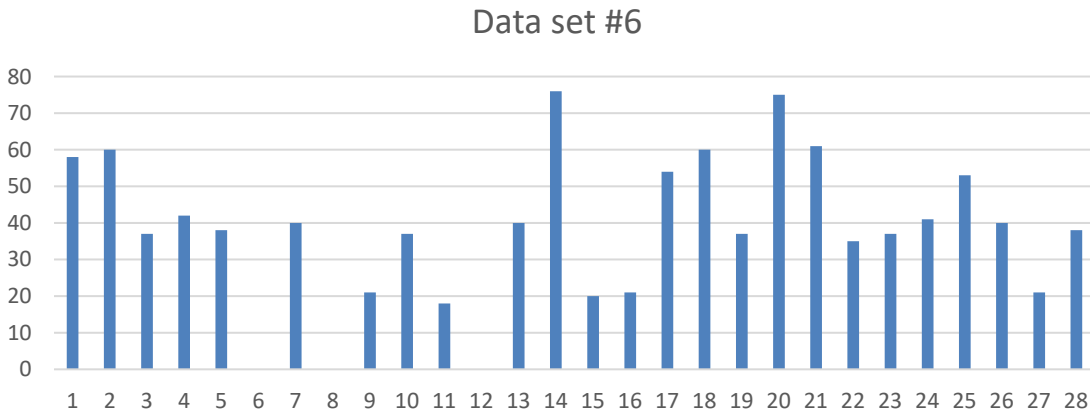


Figure 7. Resource Allocation Distribution Extracted from the Longest-Duration Scheduling Scenarios (Data Set #6)

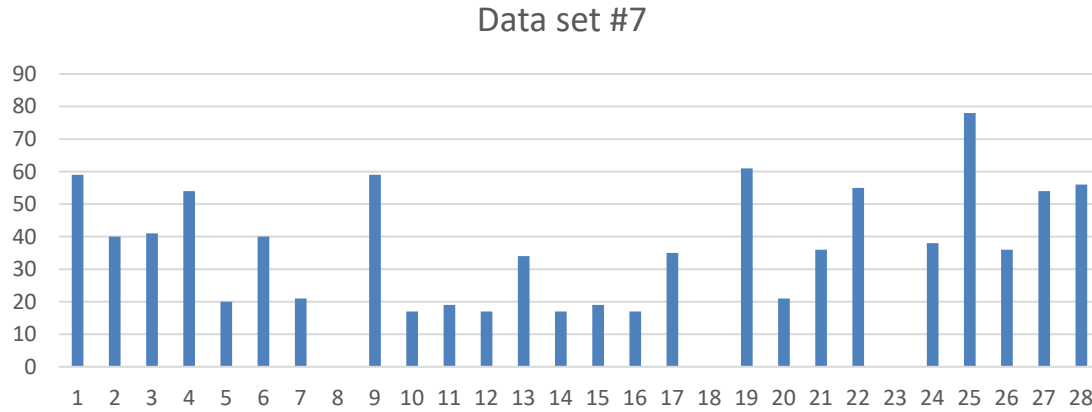


Figure 8. Resource Allocation Distribution Extracted from the Longest-Duration Scheduling Scenarios (Data Set #7)

Figures 2–8 present the workforce utilization distributions extracted from the seven worst-performing scheduling scenarios obtained from each simulation attempt. The horizontal axis represents the project activities, while the vertical axis indicates the corresponding workforce utilization levels assigned to each activity. These charts provide a visual representation of workforce allocation behavior under scheduling conditions associated with significant project duration deterioration.

A comparison of the seven datasets reveals substantial variability in workforce allocation patterns across activities. Although each simulation attempt generated different workforce configurations, the resulting utilization profiles exhibit a common characteristic: workforce resources are distributed unevenly among project activities, creating localized shortages within specific parts of the project network. This observation suggests that poor scheduling performance is not caused by a uniform reduction in workforce allocation but rather by the concentration of resource deficiencies within particular activities.

Another notable finding is that several activities repeatedly exhibit very low workforce utilization levels across multiple datasets. In many cases, these activities receive either no workforce allocation or only a minimal workforce assignment despite being embedded within the project dependency structure. Such conditions indicate the presence of severe resource deficiencies that may disrupt workflow continuity and amplify delay propagation throughout the scheduling network. The recurring appearance of these low-utilization activities across independent simulation attempts suggests the existence of underlying operational patterns rather than random workforce allocation effects.

The results therefore provide preliminary evidence that workforce allocation behavior contains identifiable and repeatable characteristics associated with schedule deterioration. More importantly, the observed recurrence of low-utilization activities supports the hypothesis that workforce bottlenecks can be systematically identified through operational data analysis. Consequently, the activities exhibiting workforce utilization values of zero or one were subsequently classified as resource-deficient activities and selected for further evaluation. The aggregation of these resource-deficient activities across all datasets forms the basis for the workforce bottleneck occurrence analysis presented in the following section.

While the workforce utilization distributions presented in Figures 2–8 provide insight into workforce allocation behavior under adverse scheduling conditions, individual datasets alone are insufficient to identify dominant operational bottlenecks. Therefore, a subsequent aggregation procedure was performed by compiling all resource-deficient activities identified across the seven simulation attempts. As defined previously, resource-deficient activities correspond to activities exhibiting workforce utilization values of zero or one within the selected worst-performing scheduling scenarios. The occurrence frequency of each resource-deficient activity was then calculated to determine how consistently an activity appeared under conditions associated with schedule deterioration. The resulting frequency distribution is presented in Figure 9.

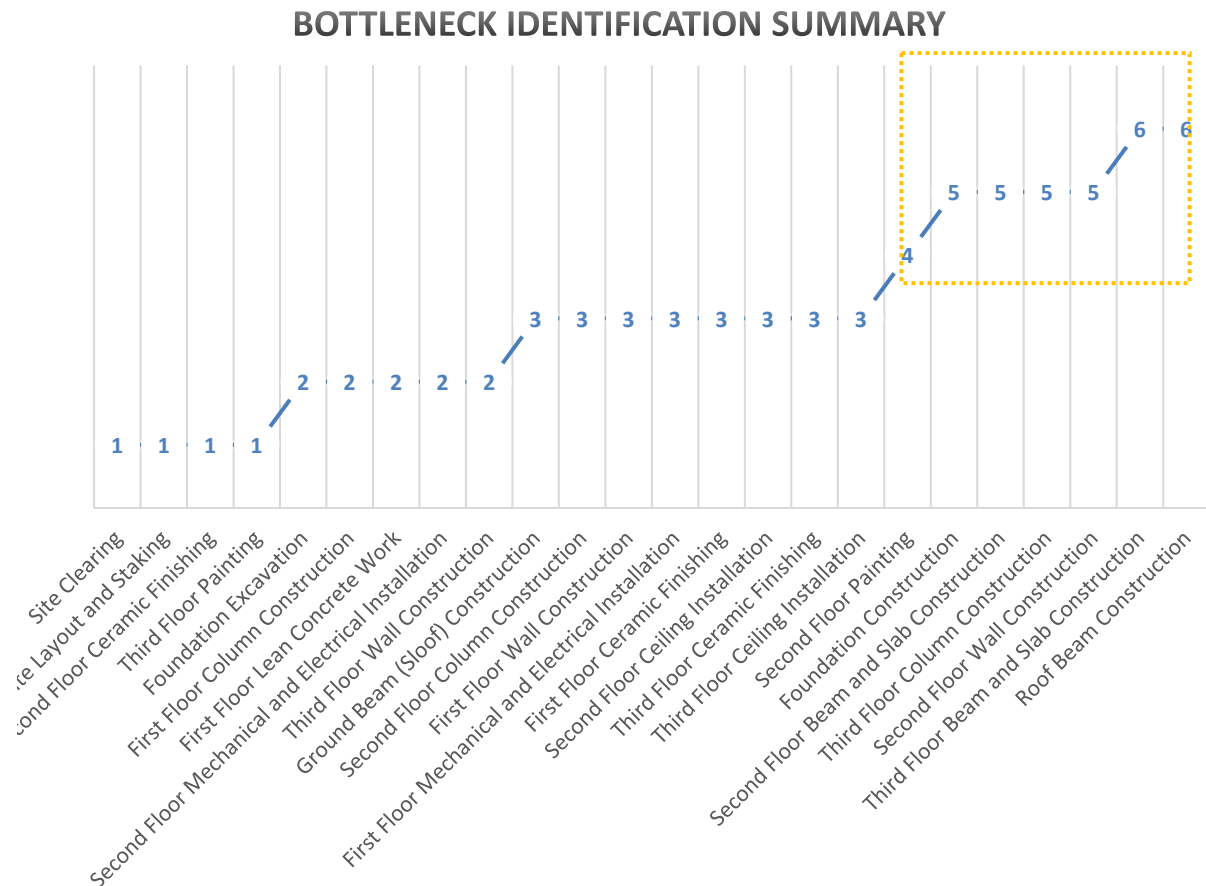


Figure 9. Recurring Resource-Deficient Activities and Workforce Bottleneck Occurrence Profile

Figure 9 presents the workforce bottleneck occurrence profile obtained from the aggregation of resource-deficient activities across all simulation attempts. The horizontal axis represents project activities, while the vertical axis indicates the frequency with which each activity appeared as a resource-deficient activity within the selected worst-performing scheduling scenarios. Higher occurrence frequencies indicate stronger bottleneck characteristics because the activity repeatedly emerged under conditions associated with prolonged project durations.

The results reveal a clear differentiation among activities in terms of their contribution to schedule degradation. Several activities exhibit relatively low occurrence frequencies, indicating that workforce deficiencies associated with these activities occurred only sporadically and therefore contributed less consistently to adverse scheduling outcomes. In contrast, a smaller group of activities repeatedly emerged as resource-deficient activities across multiple simulation attempts, suggesting a stronger relationship with project delay formation.

Among all activities, Roof Beam

Construction and Third Floor Beam and Slab Construction exhibit the highest occurrence frequencies, each appearing six times as resource-deficient activities. These are followed by Third Floor Column Construction, Second Floor Wall Construction, Second Floor Beam and Slab Construction, and Foundation Construction, which each appeared five times. The repeated occurrence of these activities suggests that workforce shortages within these operations have a greater tendency to generate schedule deterioration than shortages occurring elsewhere in the project network. Notably, most of the dominant bottlenecks are associated with structural activities, indicating that workforce deficiencies occurring within structurally interconnected operations have a greater potential to propagate delays throughout the project schedule.

The occurrence profile also reveals that bottleneck formation is not uniformly distributed across the project network. Instead, workforce deficiencies tend to concentrate within a limited subset of activities that repeatedly emerge under poor-performing

scheduling conditions. This finding supports the premise that schedule degradation is driven not only by network topology or critical path logic but also by recurring workforce allocation deficiencies embedded within the operational structure of the project. More importantly, the results demonstrate that workforce allocation behavior contains observable and repeatable patterns that can be systematically extracted from scheduling data. The recurring appearance of specific activities as resource-deficient activities across independent simulation attempts provides empirical evidence that operational constraints are not entirely random phenomena. Rather, they exhibit identifiable behavioral patterns that can be represented analytically and transformed into operational knowledge. This capability forms the foundation of the proposed operational intelligence framework, where scheduling data are utilized not only to monitor project performance but also to reveal underlying operational mechanisms contributing to project delays.

4. Discussion

The results demonstrate that workforce bottlenecks are not randomly distributed across construction activities but emerge through recurring operational patterns that can be systematically identified from scheduling data. Across seven independent simulation attempts, different workforce allocation combinations generated different project durations, alternative critical path realizations, and varying workforce utilization profiles. Despite these variations, several activities repeatedly appeared as resource-deficient activities within the worst-performing scheduling scenarios. This recurrence suggests that schedule deterioration is not solely the consequence of isolated workforce shortages but is associated with identifiable operational behaviors embedded within the project execution system. These findings are consistent with previous studies emphasizing that bottlenecks often arise from complex interactions among project resources, operational constraints, and workflow dependencies rather than from individual activities alone (Karimi et al., 2024; Panahi et al., 2023; Thekinen et al., 2023).

An important observation is that the bottleneck occurrence profile remained relatively stable despite the diversity of workforce allocation configurations explored during the simulation process. Activities exhibiting high bottleneck frequencies consistently emerged under unfavorable scheduling conditions, indicating that certain operational constraints possess a stronger influence on project performance than others. This finding suggests that workforce allocation behavior contains underlying structures that can be revealed through repeated scenario exploration. Rather than representing random scheduling outcomes, the identified bottlenecks reflect recurring operational characteristics associated with delay formation and workforce imbalance. Such observations extend existing bottleneck management studies by demonstrating that bottleneck identification can be derived analytically from scheduling behavior rather than relying solely on field observations or expert judgment (Karimi et al., 2024; Panahi et al., 2023).

The findings further indicate that project delays cannot be fully explained by conventional critical path logic alone. Traditional scheduling approaches focus primarily on identifying activities that govern project completion under a single schedule configuration (Singh, 2015; Kurniawati and Wisena, 2023). In contrast, the proposed framework evaluates a population of scheduling outcomes generated under different workforce allocation conditions. This perspective enables the identification of workforce-sensitive activities that repeatedly contribute to poor project performance, regardless of whether they appear within a particular critical path realization. Consequently, the analysis extends schedule evaluation from deterministic activity sequencing toward a broader understanding of operational behavior within construction systems. This observation aligns with recent developments in AI-assisted scheduling and data-driven project analytics, which increasingly emphasize dynamic operational interactions rather than static schedule representations (Ghasemi and Keihani, 2025; Le and Jeong, 2020; Hatami et al., 2022; Jha et al., 2022; Pourrahimian et al., 2024; Guo, 2025; Roy et al., 2025).

More importantly, the study provides evidence that operational knowledge can be extracted from scheduling data through analytical exploration of workforce allocation scenarios. The bottleneck occurrence profile generated from the aggregation of resource-deficient activities represents a form of operational knowledge that does not exist within any individual schedule. Instead, it emerges from the collective interpretation of multiple scheduling outcomes and their associated workforce allocation behaviors. This capability represents a fundamental shift from conventional schedule monitoring toward operational intelligence, where project data are not merely used to report performance but are analyzed to reveal the underlying operational mechanisms responsible for that performance. Similar transitions have recently been discussed within the broader context of intelligent decision-making, construction analytics, and digital project management systems (Ibrahim et al., 2025; Mohammadi et al., 2025; Memon et al., 2025; Soofastaei, 2025).

Although the present study does not implement artificial intelligence as a predictive or learning model, the results provide empirical evidence that construction scheduling contains observable, measurable, and repeatable behavioral patterns. The recurring emergence of resource-deficient activities across independent simulation attempts demonstrates that operational constraints possess

an identifiable analytical structure that can be systematically represented and quantified. This finding is particularly important because it establishes the existence of a learnable operational foundation within construction scheduling. In other words, the study demonstrates that the prerequisite conditions required for future artificial intelligence applications are present within project operational data. The identified recurring patterns therefore provide a theoretical and analytical basis for future research involving machine learning, digital twins, and intelligent decision-support systems for construction workforce management (Chen et al., 2025; Gill et al., 2024; Unegbu and Yawas, 2025; Tolba et al., 2025; Mohammadi et al., 2025; Memon et al., 2025; Soofastaei, 2025).

Ultimately, the principal contribution of this research lies not in identifying specific bottleneck activities, but in demonstrating that construction operations contain recurring behavioral patterns that can be transformed into operational knowledge through analytical procedures. The existence of these patterns supports the feasibility of operational intelligence as a future paradigm for construction project control, where workforce allocation decisions can be informed not only by experience and intuition but also by systematically extracted operational insights. In this regard, the proposed framework provides an initial analytical foundation for future AI-enabled construction management systems capable of continuously identifying operational constraints, learning from project behavior, and supporting adaptive decision-making throughout project execution (Chen et al., 2025; Mohammadi et al., 2025; Memon et al., 2025; Soofastaei, 2025; Yogi et al., 2026).

5. Conclusion

This study developed a mathematical workforce bottleneck analytics framework to support the transition from conventional schedule monitoring toward operational intelligence in construction project management. Through the generation of multiple workforce allocation scenarios using a dynamic critical path network, the framework enabled the systematic identification of resource-deficient activities and recurring bottleneck patterns associated with schedule deterioration. The results demonstrate that project delays are influenced not only by activity dependencies and critical path logic but also by recurring workforce allocation deficiencies embedded within the operational structure of the project. More importantly, the repeated emergence of specific resource-deficient activities across independent simulation scenarios provides empirical evidence that construction scheduling contains observable, measurable, and repeatable operational patterns that can be systematically extracted and transformed into operational knowledge. These findings establish a valid analytical foundation for operational intelligence in construction management and highlight the potential for future integration of artificial intelligence, machine learning, digital twins, and advanced analytics to support adaptive workforce management, proactive bottleneck detection, and intelligent project control throughout construction execution.

Acknowledgements

The authors gratefully acknowledge this financial support by the Budget Implementation List (DIPA) of University of Riau through Research Grant Program 2026

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