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How Critical Chain Project Management and IoT-Based Predictive Maintenance Enhance Infrastructure Delivery: A Case Study of Mid-Scale Bridge Construction in Central Java

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Abstrak. *Studi ini mengeksplorasi bagaimana integrasi antara Critical Chain Project Management (CCPM) dan pemeliharaan prediktif berbasis IoT dapat meningkatkan pelaksanaan proyek dan keberlanjutan infrastruktur pada proyek pembangunan jembatan skala menengah di Indonesia. Penelitian ini menggunakan pendekatan studi kasus tunggal kualitatif, dengan fokus pada proyek pembangunan Jembatan Trasan II di Jawa Tengah. Data dikumpulkan melalui observasi langsung, wawancara mendalam dengan empat personel kunci proyek, serta dokumen sekunder seperti jadwal proyek, laporan Mutual Check (MC-0 dan MC-1), dan data rencana pemeliharaan. Hasil menunjukkan bahwa penerapan CCPM meningkatkan kinerja penjadwalan proyek dengan mengurangi waktu menganggur dan meningkatkan fleksibilitas melalui manajemen buffer. Penerapan mutual check membantu menyelaraskan rencana dengan kondisi lapangan dan memperkuat kontrol kualitas. Integrasi IoT dalam pemeliharaan menghasilkan pengurangan biaya tahunan hingga 40% dan memperpanjang umur layanan jembatan hingga 20 tahun. Penelitian ini merupakan salah satu yang pertama secara empiris mengkaji sinergi antara CCPM dan pemeliharaan berbasis IoT dalam proyek infrastruktur nyata di negara berkembang. Studi ini menawarkan kerangka praktis bagi manajer proyek untuk mengoptimalkan hasil proyek secara berkelanjutan, serta menunjukkan bagaimana kombinasi strategi penjadwalan modern dan pemantauan digital dapat diterapkan secara efektif untuk meningkatkan efisiensi dan keberlanjutan di bawah keterbatasan sumber daya.*

Kata kunci: *Critical Chain Project Management; IoT; Pemeliharaan Prediktif; Infrastruktur; Studi Kasus; Penjadwalan Proyek.*

Abstract. *This study explores how the integration of Critical Chain Project Management (CCPM) and IoT-based predictive maintenance can enhance both project execution and infrastructure sustainability in a mid-scale bridge construction project in Indonesia. A qualitative single-case study approach was employed, focusing on the Trasan II Bridge construction project in Central Java. Data were collected through direct observations, in-depth interviews with four key project personnel, and secondary documents including scheduling records, Mutual Check reports (MC-0 and MC-1), and maintenance planning data. The study found that CCPM significantly improved scheduling performance by reducing idle time and increasing flexibility through buffer management. The use of mutual checks helped align planning with field conditions and enhanced quality control. The integration of IoT in maintenance led to a 40% reduction in annual costs and extended the projected service life of the bridge by up to 20 years. This research is among the first to empirically examine the synergy between CCPM and IoT-based maintenance in a real-world infrastructure project in a developing country. It provides a practical framework for project managers seeking to optimize lifecycle outcomes. The study demonstrates how modern project scheduling and digital monitoring can be effectively combined to improve delivery and sustainability under resource constraints.*

Keywords: *Critical Chain Project Management; IoT; Predictive Maintenance; Infrastructure; Case Study; Project Scheduling.*

Introduction

Infrastructure projects such as bridge construction play a vital role in enhancing regional connectivity (Bhandari *et al*., 2025; Cervantes *et al*., 2024), reducing transportation bottlenecks, and promoting economic development (Li *et al*., 2025). Effective project scheduling and maintenance management are critical factors in ensuring that such projects are delivered on time, within budget, and with long-term structural integrity. Project scheduling, when executed poorly, has been found to contribute to delays, cost overruns, and operational inefficiencies (Durdyev & Hosseini, 2019; Koulinas *et al*., 2020; Yaseen *et al*., 2020). To mitigate these risks, the Critical Chain Project Management (CCPM) method has emerged as a promising approach that accounts for resource constraints and integrates buffer management to reduce project delays (Anastasiu *et al*., 2023; Leach, 1999). Simultaneously, technological advancements in the Internet of Things (IoT) have enabled a shift from reactive to predictive maintenance strategies, which can significantly improve infrastructure longevity and operational efficiency (Lu *et al*., 2016).

Although Critical Chain Project Management (CCPM) has been widely recognized for its ability to improve scheduling performance and resource utilization in construction projects (Umble *et al*., 2006; Yaghootkar & Gil, 2012; Zou *et al*., 2007) most of its practical applications have been limited to complex, capital-intensive projects situated in urban environments, leaving mid-scale infrastructure initiatives in developing regions relatively underexplored. For instance, Yaghootkar and Gil (2012) examined CCPM's implementation in multi-project environments, revealing its effectiveness in mitigating resource conflicts but focusing primarily on high-tech industrial construction. Similarly, IoT-based predictive maintenance has been extensively studied in infrastructure asset management, particularly in advanced systems such as bridge health monitoring through wireless sensors (Al-Ali *et al*., 2024; Him *et al*., 2019) and AI-driven visual inspections (Shahrivar *et al*., 2025). Projects like the Msikaba Bridge in South Africa have integrated digital twin and IoT technologies to monitor structural integrity in real time (de Kock, 2023). However, these studies emphasize high-budget megaprojects and do not address the operational dynamics of resource-constrained rural or semi-urban infrastructure initiatives. While prior studies have explored CCPM and IoT in isolation, few have examined how their integration may complement each other in enhancing both the execution and long-term performance of infrastructure projects (e.g., (Al-Ali *et al*., 2024; Anastasiu *et al*., 2023; Him *et al*., 2019; Shahrivar *et al*., 2025; Yaghootkar & Gil, 2012). Specifically, the literature lacks empirical research that investigates CCPM's impact on schedule efficiency while simultaneously evaluating how IoT-based predictive maintenance supports lifecycle cost control and asset longevity. This integration becomes particularly relevant in mid-scale public projects in developing countries, where budget constraints and workforce limitations demand more adaptive and resource-efficient approaches (Asif *et al*., 2024; Irfan *et al*., 2021; Varriale *et al*., 2024).

Despite the growing body of literature on CCPM and IoT separately, there is a lack of integrated research that combines these two approaches in real-world infrastructure projects, particularly in the context of mid-scale bridge construction in developing countries. The key question remains: how can the synergy between CCPM and IoT-based predictive maintenance be leveraged to optimize both project scheduling and long-term infrastructure sustainability under constrained conditions, how is the effectiveness of project scheduling, how does the application of mutual checks help project control? and how is maintenance performed and what are the results? To address this gap, the present study investigates the implementation of Critical Chain Project Management in conjunction with IoT-based maintenance in the Trasan II Bridge construction project in Klaten, Central Java. The study aims to explore how CCPM influences the scheduling efficiency of the project, how IoT-based predictive maintenance contributes to its lifespan and operational cost efficiency, and how the integration of both methods can enhance project outcomes in comparable infrastructure projects.

The Trasan II Bridge project provides a suitable case due to its mid-scale scope, rural location, and implementation of both CCPM and IoT elements under budgetary limitations. Its practical context allows exploration of theoretical integration in a real-world setting, making the findings relevant for similar projects in other developing regions.

Literature Review

Concepts of Project and Project Lifecycle

A project is defined as a temporary endeavor undertaken to create a unique product, service, or result (Project Management Institute, 2021). Unlike routine operations, projects are characterized by a defined beginning and end, specific objectives, resource constraints, and a set of interrelated tasks designed to achieve targeted outcomes (Kerzner, 2017). In the field of construction, projects commonly involve the development of physical infrastructure such as roads, bridges, and buildings (Klareld, 2021; Zou *et al*., 2007), with distinct stages that require coordinated management across various disciplines.

The concept of the project lifecycle is foundational in project management theory. It typically comprises five major phases: initiation, planning, execution, monitoring and controlling, and closing (Turner, 2016). Each phase serves a critical function in ensuring project success. The initiation phase involves identifying the project's value proposition and feasibility; the planning phase includes scope definition, scheduling, budgeting, and risk planning; the execution phase focuses on delivering project deliverables; the monitoring and controlling phase ensures that performance aligns with the baseline; and the closing phase involves finalizing all activities and formally completing the project (Project Management Institute, 2021). In infrastructure projects, lifecycle management is particularly important due to the long-term operational implications of design and construction decisions (Wang *et al*., 2020). Delays or inefficiencies in one phase can ripple into others, making lifecycle thinking essential for effective governance and sustainability of public works (Morris, 2013). As such, understanding the structure and dynamics of project lifecycles forms the basis for selecting appropriate management tools and methodologies throughout a project's duration.

Planning and Scheduling in Project Execution

Project planning is a fundamental process in project management, involving the identification of objectives, the definition of scope, the estimation of time and costs, and the development of strategies to deliver project outcomes effectively (Kerzner, 2017). In the construction industry, effective planning is particularly critical due to the complexity and scale of tasks, the involvement of multiple stakeholders, and the resource-intensive nature of operations. A well-structured project plan serves as a blueprint that guides the coordination of activities and helps mitigate risks associated with uncertainty and change (PMI, 2017). Scheduling, as a core component of project planning, refers to the process of determining the sequence and timing of activities to ensure efficient use of resources and timely project completion. Traditional scheduling techniques such as the Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) have long been employed to model task dependencies, estimate durations, and identify critical activities (Turner, 2016). These methods provide visual representations such as Gantt charts and network diagrams that support decision-making and performance tracking.

However, despite their widespread use, conventional scheduling tools have been criticized for their limitations in managing uncertainties and resource constraints effectively (Peng *et al*., 2025). In dynamic environments like infrastructure construction, unanticipated delays, supply chain disruptions, and labor shortages can significantly impact the reliability of baseline schedules. This has led to the growing interest in more adaptive and constraint-based scheduling methodologies, such as Critical Chain Project Management (CCPM), which integrates resource availability and buffer management into scheduling decisions (Anastasiu *et al*., 2023).

Critical Chain Project Management (CCPM)

Critical Chain Project Management (CCPM) is a project planning and control method developed by Eliyahu Goldratt based on the Theory of Constraints. Unlike traditional methods such as the Critical Path Method (CPM), CCPM focuses on resource constraints and uncertainty by using buffer management to protect the project schedule (Herroelen & Leus, 2001). It identifies the critical chain—the longest chain of dependent tasks considering both task and resource dependencies—and adds time buffers to absorb delays. Several studies have shown the advantages of CCPM in improving project performance. For example, Anastasiu *et al.* (2023) applied CCPM to a housing construction project and reported a 20% reduction in project duration compared to CPM. This improvement was most visible in the finishing phase, such as drywall installation and painting. Leach (1999) also demonstrated that CCPM helps minimize delays by discouraging multitasking and encouraging early task completion. In complex infrastructure settings, CCPM's buffer strategies allow project managers to absorb delays and reduce idle time of machinery and labor (Durdyev & Hosseini, 2019). Previous empirical studies demonstrate that CCPM reduces schedule variance and enhances control in dynamic environments (Koulinas *et al.*, 2020).

IoT-Based Predictive Maintenance in Infrastructure

Predictive maintenance (PdM) represents a proactive approach to infrastructure management, aiming to anticipate and address potential failures before they occur (Benhanifia *et al.*, 2025; Murtaza *et al.*, 2024). The integration of the Internet of Things (IoT) into PdM has revolutionized this field by enabling real-time monitoring and analysis of structural health parameters. IoT devices, such as sensors and actuators, collect data on variables like vibration, temperature, and strain, which are then analyzed to predict maintenance needs, thereby reducing downtime and extending the lifespan of infrastructure components (Allioui & Mourdi, 2023; Aminzadeh *et al.*, 2025).

In the context of bridge infrastructure, IoT-based PdM systems have demonstrated significant benefits. For instance, Al-Ali *et al.* (2024) developed a wireless, low-cost bridge health monitoring system that utilizes various sensors to assess structural integrity. Their system incorporates a fuzzy logic algorithm to classify bridge health status, providing early warnings through a mobile application interface. This approach not only enhances safety but also optimizes maintenance schedules and resource allocation. Moreover, the application of IoT in PdM extends to the broader construction industry.

By leveraging data analytics and machine learning, IoT-enabled systems can predict equipment failures, optimize maintenance tasks, and improve overall operational efficiency (Elkateb *et al.*, 2024; Murtaza *et al.*, 2024). Such advancements contribute to the development of smart infrastructure, where continuous monitoring and predictive analytics ensure structural reliability and performance. Despite these advantages, most literature treats IoT maintenance separately from scheduling concerns. There is a lack of integrated models that combine digital maintenance systems with planning methodologies like CCPM to optimize lifecycle performance holistically (Cervantes *et al.*, 2024; Lu *et al.*, 2016).

Research Methodology

This research adopts a qualitative, single-case study design based on the framework proposed by Eisenhardt (1989), which is widely used to explore complex, context-specific phenomena in real-life settings. The case under investigation is the bridge construction project in Juwiring Village, Klaten, Central Java, conducted by PT Raharja Mulia. This case was selected due to its relevance in demonstrating how project scheduling and maintenance practices are implemented and adapted in infrastructure development at the local level.

Data Collection

The study relies on both primary and secondary data. Primary data were collected through direct observation and semi-structured interviews with

four key informants who were directly involved in the project execution:
1) Ichsan Fadli – Project Manager
2) Dwi Marsono Widodo – Project Manager
3) Yoga Pratama Putra – Site Supervisor
4) Agus Setyanta – Technical Assistant

The interview protocol was semi-structured, allowing respondents to elaborate on project scheduling, quality control, and maintenance integration. To guide us during the interviews and ensure the discussion remained focused, we developed an interview protocol consisting of a list of questions based on a priori constructs. While this list provided structure, interviews were conducted flexibly, allowing new questions to emerge during the conversation. We also conducted follow-up site visits when interesting issues relevant to the subject arose (Glaser & Strauss, 2017).

Data were triangulated through pattern matching and document analysis to validate emerging themes and ensure reliability (Yin, 2020). The interviews were conducted in person and focused on the planning, execution, and control mechanisms used in the project, with particular attention to scheduling strategies, resource management, and quality assurance processes. Observations were made throughout the construction period, allowing the researcher to gain contextual insights into the physical environment, workflow, and team interactions on-site. Secondary data were obtained from official project documentation, including:
1) Mutual Check (MC-0 and MC-1) Reports
2) Budget Plan (Rencana Anggaran Biaya/RAB)
3) Work Volume Recapitulation
4) Technical Documentation and Photographic Evidence

Mutual Check documents play a strategic role in verifying project accuracy and controlling execution quality. Two distinct types were used in this project: Mutual Check 0 (MC-0) and Mutual Check 1 (MC-1). MC-0 is conducted prior to the physical execution of the project. It includes field measurements to match design drawings with actual conditions, recalculations of work volume and material needs (e.g., concrete, steel, asphalt), and revised cost estimates based on on-site realities. The primary goal of MC-0 is to align planning documents with field conditions, preventing significant deviations and minimizing contract modifications (Dwianto *et al.*, 2023; Willar *et al.*, 2023). MC-1, by contrast, is carried out after project execution to verify that all construction elements meet technical specifications. This stage involves physical inspection of key components such as foundations, abutments, and the superstructure, along with precise measurement verification and a final financial summary. MC-1 ensures that all work is compliant with quality standards before the project advances to final handover or next phases (Dwianto *et al.*, 2023; Willar *et al.*, 2023; Zou *et al.*, 2007).

Results and Discussion

Results

This section presents the key findings obtained through interviews, field observations, and secondary document analysis from the *"Juwiring"* Bridge construction project. The results are categorized into three major themes: (1) project planning and scheduling practices, (2) verification through mutual check mechanisms, and (3) field-level maintenance and quality assurance strategies.

Scheduling Performance and CCPM Application

The application of Critical Chain Project Management (CCPM) played a key role in optimizing the project schedule. The use of buffer management enabled the team to absorb delays without affecting the overall project timeline. According to Ichsan Fadli, Project Manager,

"The buffer system in CCPM gave us flexibility. Small disruptions in the field didn't affect the overall target. That was key to staying on schedule." Ichsan Fadli, Project Manager.

Field documentation supports this claim, as shown in Table 1. The total duration of the project was 5 months and 26 days—faster than the original 6-month plan. Three major phases mobilization, excavation, and structural works each experienced a time reduction of 4 weeks due to efficient resource coordination, favorable weather, and timely material delivery. However, interviews revealed that favorable weather conditions also played a significant role in minimizing delays. As noted by Dwi Marsono,

"We were fortunate that the rainy season came late. Dry weather allowed us to pour concrete and excavate continuously without interruption." Dwi Marsono, Project Manager.

Thus, while CCPM provided structural scheduling efficiency, external factors such as climate conditions also contributed. This interplay should be considered when evaluating CCPM's impact in tropical regions where weather variability can greatly affect timelines.

Table 1. Comparison of Planned vs. Actual Schedule in Trasan II Bridge Construction

No.	Main Activity	Planned Duration	Actual Duration	Deviation	Reason
1	Mobilization	25 Weeks	21 Weeks	-4 Weeks	Efficient resource use
2	Excavation (0-2m)	11 Weeks	7 Weeks	-4 Weeks	Favorable weather
3	Concrete & Steel Works	16 Weeks	12 Weeks	-4 Weeks	Timely materials, skilled labor
4	Finishing	2 Weeks	2 Weeks	0 Weeks	Effective coordination

Dwi Marsono Widodo, another project manager, added.

"By focusing only on the critical chain, we avoided resource bottlenecks. There were fewer idle periods, and that really boosted productivity." Dwi Marsono, Project Manager.

Quality Assurance through Mutual Check Mechanism

To ensure schedule alignment and technical compliance, the project employed two quality control tools: Mutual Check 0 (MC-0) and Mutual Check 1 (MC-1). MC-0 was conducted before physical construction began, involving field measurement and recalculations of material volume. This process minimized the risk of contract modifications and scope creep.

"MC-0 helped align our drawings with actual field conditions. It prevented material miscalculations and rework, saving both time and cost." Yoga Pratama, Field Supervisor.

Secondary data indicate that by identifying discrepancies before execution, MC-0 prevented at least two major design revisions which would have cost approximately Rp 15 million in rework materials and extended the schedule by 10 working days. MC-1 similarly verified output dimensions, reducing post-construction rectification costs. Although the benefits were mostly qualitative, these cost savings provide preliminary quantitative support for the effectiveness of the mutual check system. MC-1 was performed after construction, to verify dimensional and structural accuracy. Inspection tools were used to measure abutments, deck dimensions, and concrete curing. Documentation from this process supported final project reporting and payment reconciliation.

Predictive Maintenance and IoT Integration

After handover, bridge maintenance was outsourced to a third-party vendor specializing in sensor-based predictive systems. IoT devices were installed on key structural elements to monitor stress, vibration, and corrosion levels in real time. This data allowed proactive maintenance scheduling and reduced the risk of catastrophic failure. As shown in Table 2, the predictive maintenance model significantly extended the projected lifespan of the bridge while optimizing yearly maintenance expenses.

Table 2. Estimated Lifespan and Cost Comparison of Maintenance Strategies

No.	Maintenance Strategy	Estimated Lifespan	Annual Cost	Savings vs No Maintenance
1	No Maintenance	10-15 years	Rp 0	-
2	Routine Inspections (6 month)	30 years	Rp 10.000.000	Rp 1.2 billion over lifespan
3	Coating & Steel Component Care	40 years	Rp 25.000.000	Rp 900 million
4	Scheduled Repairs & Predictive System	50 years	Rp 40.000.000	Highest cost-efficiency

Agus Setyanta, Technical Assistant, explained: *"We selected the vendor based on their experience with IoT-based inspections. Real-time monitoring allows us to catch early signs of wear and plan maintenance accordingly."* Agus Setyanta, Technical Assistant.

This is further supported by Table 3, which compares operational benefits with and without IoT integration.

Table 3. Comparison of Bridge Maintenance with and without IoT

No.	Indicator	Without IoT	With IoT
1	Inspection Frequency	Every 6 months	Daily via real-time startup
2	Damage Detection Method	Manual	Automated via sensors & AI
3	Annual Maintenance Cost	Rp 50 million	Rp 30 million (40% savings)
4	Scheduled Repairs & Infrastructure Lifespan	30 years	50 years

Ichsan Fadli highlighted the broader benefits:

"Routine maintenance supported by IoT can reduce major failure risk by up to 70%. It gives us peace of mind and better long-term planning." Ichsan Fadli, Project Manager.

The synergy between CCPM scheduling and IoT-enabled maintenance significantly improved the project's time, quality, and cost outcomes, demonstrating how strategic planning and modern technology can complement each other in infrastructure development.

Discussion

This study explored how the integration of Critical Chain Project Management (CCPM) and IoT-based predictive maintenance contributed to the scheduling efficiency and long-term sustainability of a mid-scale infrastructure project. The findings from the Trasan II Bridge construction project provide valuable insights into how these two approaches can complement one another under constrained project conditions. The implementation of CCPM resulted in tangible improvements to scheduling efficiency. Project activities, including excavation and structural works, were completed ahead of schedule, supported by the effective use of time buffers and resource-focused planning. These findings echo previous studies that emphasize CCPM's ability to manage uncertainty and reduce project duration by optimizing resource allocation and minimizing multitasking (Herroelen & Leus, 2001; Leach, 1999). The triangulated perspectives from project managers further confirm that focusing on the critical chain helped eliminate idle time and improved productivity result that reinforces the practical value of CCPM in infrastructure projects with limited flexibility. In addition to planning and scheduling, the application of mutual check mechanisms contributed significantly to project control and quality assurance. The MC-0 process allowed for early detection of discrepancies between design plans and field conditions, helping to prevent rework and contract modifications. Meanwhile, MC-1 served as a formal post-construction verification step to ensure compliance with technical standards. These mechanisms not only strengthened transparency but also enhanced stakeholder accountability, reflecting the importance of iterative control processes in construction management (Dwianto *et al.*, 2023; Willar *et al.*, 2023). Equally important is the role of predictive maintenance, which was implemented through a third-party vendor using IoT-based monitoring systems. Real-time sensor data on structural health indicators enabled early detection of potential failures, reducing the risk of costly repairs. The financial analysis indicated that IoT-based maintenance lowered annual maintenance costs by up to 40% and extended the projected lifespan of the bridge from 30 to 50 years. These outcomes are consistent with recent literature that highlights the transformative role of IoT in infrastructure maintenance, particularly through automation, continuous diagnostics, and data-driven scheduling (Al-Ali *et al.*, 2024).

Despite these benefits, implementing IoT-based maintenance is not without challenges. Initial investment in sensor hardware and the need for technical training among local maintenance personnel presented barriers during the project. Similarly, the adoption of CCPM required orientation sessions for planners unfamiliar with buffer-based scheduling, indicating a learning curve for field teams. These issues highlight the need for capacity building when deploying integrated methods in public infrastructure projects. Most notably, this study demonstrates that CCPM and IoT do not operate in isolation but can be synergistically integrated to produce superior project outcomes. CCPM enhances execution by managing time and resources effectively, while IoT contributes to sustainability through intelligent maintenance. When combined, they form a comprehensive project delivery strategy that aligns execution efficiency with long-term performance. This synergy is particularly relevant for infrastructure projects in developing countries, where resource limitations and asset longevity are pressing concerns. In sum, the Trasan II Bridge case shows how modern project management techniques can be adapted and applied in real-world settings to improve performance across the full lifecycle of an infrastructure project. These findings suggest that the integration of CCPM and IoT is not only technically viable but also strategically advantageous for enhancing resilience, reliability, and sustainability in public works. Comparatively, infrastructure projects in urban settings with higher budgets such as the Msikaba Bridge in South Africa have used digital twins and AI tools extensively (de Kock, 2023). However, the Trasan II case demonstrates that with thoughtful adaptation, similar outcomes can be achieved at lower cost. Practitioners in developing countries can adopt a hybrid approach, leveraging basic IoT and simplified CCPM tools to achieve measurable improvements in delivery and resilience.

Conclusion

This study explored the integration of Critical Chain Project Management (CCPM) and IoT-based predictive maintenance in the Trasan II Bridge project in Central Java. The findings show that CCPM improved scheduling efficiency by minimizing idle time and managing delays through buffer strategies. Mutual checks (MC-0 and MC-1) enhanced project control and ensured alignment between planning and field implementation. Meanwhile, IoT-enabled maintenance reduced long-term costs and extended the infrastructure's lifespan through real-time monitoring and early fault detection. These results suggest that combining CCPM and IoT offers a practical and effective framework for infrastructure development, particularly in resource-constrained environments. Project managers can apply this approach to improve both execution and post-construction performance, providing greater value over the full lifecycle of public works. To address budget limitations, practitioners may consider phased implementation strategies starting with simplified CCPM training using Excel-based buffer tracking and adopting low-cost sensor technologies such as passive RFID or open-source IoT kits (e.g., Arduino-based SHM). Partnerships with local universities or tech incubators may also help reduce implementation costs and build capacity.

This research successfully addressed the initial questions regarding scheduling efficiency, project control, and infrastructure sustainability. However, as a single-case study, the findings may not be universally generalizable. Future research should examine longitudinal impacts across different project sizes and funding models. Moreover, integrating system dynamics modeling or agent-based simulations could yield deeper insights into how CCPM and IoT interact under varying policy, climate, and workforce scenarios. Exploring cross-sector applications such as in water treatment or renewable energy infrastructure may also expand the generalizability and strategic relevance of this hybrid approach. Practitioners are encouraged to adopt integrated planning-maintenance strategies that connect short-term project goals with long-term operational outcomes. For the academic community, this study offers a foundation to advance lifecycle-based project integration models that are both scalable and adaptive to the evolving demands of infrastructure delivery in emerging economies.

References

Al-Ali, A. R., Beheiry, S., Alnabulsi, A., Obaid, S., Mansoor, N., Odeh, N., & Mostafa, A. (2024). An IoT-based road bridge health monitoring and warning system. *Sensors*, *24*(2), 469. https://doi.org/10.3390/s24020469.

Allioui, H., & Mourdi, Y. (2023). Exploring the full potentials of IoT for better financial growth and stability: A comprehensive survey. *Sensors, 23*(19), 8015. https://doi.org/10.3390/s23198015.

Aminzadeh, A., Sattarpanah Karganroudi, S., Majidi, S., Dabompre, C., Azaiez, K., Mitride, C., & Sénéchal, E. (2025). A machine learning implementation to predictive maintenance and monitoring of industrial compressors. *Sensors, 25*(4), 1006. https://doi.org/10.3390/s25041006.

Anastasiu, L., Câmpian, C., & Roman, N. (2023). Boosting construction project timeline: The case of critical chain project management (CCPM). *Buildings, 13*(5), 1249. https://doi.org/10.3390/buildings13051249.

Asif, M., Naeem, G., & Khalid, M. (2024). Digitalization for sustainable buildings: Technologies, applications, potential, and challenges. *Journal of Cleaner Production, 450*, 141814. https://doi.org/10.1016/j.jclepro.2024.141814.

Benhanifia, A., Cheikh, Z. B., Oliveira, P. M., Valente, A., & Lima, J. (2025). Systematic review of predictive maintenance practices in the manufacturing sector. *Intelligent Systems with Applications, 26*, 200501. https://doi.org/10.1016/j.iswa.2025.200501.

Bhandari, S. B., Shahi, P. B., Sharma, R. R., & Sharma, K. K. (2025). Bridges in Nepal: Enhancing connectivity and economic development. *The Open Transportation Journal, 19*(1), e26671212357746. https://doi.org/10.2174/0126671212357746241125101606.

Cervantes, E., Matos, J., & Lantsoght, E. (2024). Bridge infrastructure in Ecuador: Challenges and solutions. *Revista de Ativos de Engenharia, 2*(2), 087–103. https://doi.org/10.29073/rae.v2i2.927.

Durdyev, S., & Hosseini, M. R. (2019). Causes of delays on construction projects: A comprehensive list. *International Journal of Managing Projects in Business, 13*(1), 20–46. https://doi.org/10.1108/IJMPB-09-2018-0178.

Dwianto, R., Mahya, H. Z., Taurano, G. A., & Wijaya, H. A. (2023). Perbandingan perhitungan MC-0 metode konvensional & building information modelling (BIM) terhadap realisasi pekerjaan. *Konstruksia, 14*(2), 109.

https://doi.org/10.24853/jk.14.2.109-118.

Eisenhardt, K. M. (1989). Building theories from case study research. *The Academy of Management Review, 14*(4), 532. https://doi.org/10.2307/258557.

Elkateb, S., Métwalli, A., Shendy, A., & Abu-Elanien, A. E. B. (2024). Machine learning and IoT-based predictive maintenance approach for industrial applications. *Alexandria Engineering Journal, 88*, 298–309. https://doi.org/10.1016/j.aej.2023.12.065.

Glaser, B. G., & Strauss, A. L. (2017). *The discovery of grounded theory: Strategies for qualitative research* (1st ed.). Routledge. https://doi.org/10.4324/9780203793206.

Herroelen, W., & Leus, R. (2001). On the merits and pitfalls of critical chain scheduling. *Journal of Operations Management, 19*(5), 559–577. https://doi.org/10.1016/S0272-6963(01)00054-7.

Him, L. C., Poh, Y. Y., & Pheng, L. W. (2019). IoT-based predictive maintenance for smart manufacturing systems. *2019 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA ASC)*, 1942–1944. https://doi.org/10.1109/APSIPAASC47483.2019.9023106.

Irfan, M., Khan, S. Z., Hassan, N., Hassan, M., Habib, M., Khan, S., & Khan, H. H. (2021). Role of project planning and project manager competencies on public sector project success. *Sustainability, 13*(3), 1421. https://doi.org/10.3390/su13031421.

Kerzner, H. (2017). *Project management: A systems approach to planning, scheduling, and controlling* (12th ed.). Wiley.

Klareld, A.-S. (2021). A reliable reflection? Challenges when documenting physical infrastructure. *Records Management Journal, 31*(2), 134–157. https://doi.org/10.1108/RMJ-11-2020-0040.

Koulinas, G., Xanthopoulos, A., Tsilipiras, T., & Koulouriotis, D. (2020). Schedule delay risk analysis in construction projects with a simulation-based expert system. *Buildings, 10*(8), 134. https://doi.org/10.3390/buildings10080134.

Leach, L. P. (1999). Critical chain project management improves project performance. *Project Management Journal, 30*(2), 39–51. https://doi.org/10.1177/875697289903000207.

Li, H., Hu, T., Ma, X., & Cheng, B. (2025). The impact of transportation infrastructure on the regional economic integration in China: A CGE analysis. *International Review of Economics & Finance, 99*, 104045. https://doi.org/10.1016/j.iref.2025.104045.

Lu, Y., Morris, K., & Frechette, S. (2016). Current standards landscape for smart manufacturing systems (No. NIST IR 8107; p. NIST IR 8107). National Institute of Standards and Technology. https://doi.org/10.6028/NIST.IR.8107.

Morris, P. W. G. (2013). *Reconstructing project management*. John Wiley & Sons.

Murtaza, A. A., Saher, A., Hamza Zafar, M., Kumayl Raza Moosavi, S., Faisal Aftab, M., & Sanfilippo, F. (2024). Paradigm shift for predictive maintenance and condition monitoring from Industry 4.0 to Industry 5.0: A systematic review, challenges, and case study. *Results in Engineering, 24*, 102935. https://doi.org/10.1016/j.rineng.2024.102935.

Peng, J., Gao, W., Li, Y., He, S., Wang, K., & Xu, M. (2025). A heuristic solution for multi-mode resource-constrained project scheduling problem with transfer times: The multi-project case. *Expert Systems with Applications, 128122*. https://doi.org/10.1016/j.eswa.2025.128122.

Project Management Institute. (2021). *The standard for project management and a guide to the project management body of knowledge (PMBOK® Guide)* (7th ed.). Project Management Institute.

Shahrivar, F., Sidiq, A., Mahmoodian, M., Jayasinghe, S., Sun, Z., & Setunge, S. (2025). AI-based bridge maintenance management: A comprehensive review. *Artificial Intelligence Review, 58*(5), 135. https://doi.org/10.1007/s10462-025-11144-7.

Turner, R. (2016). *Gower handbook of project management* (5th ed.). Routledge. https://doi.org/10.4324/9781315585741.

Umble, M., Umble, E., & Murakami, S. (2006). Implementing theory of constraints in a traditional Japanese manufacturing environment: The case of Hitachi Tool Engineering. *International Journal of Production Research, 44*(10), 1863–1880. https://doi.org/10.1080/00207540500381393.

Varriale, V., Cammarano, A., Michelino, F., & Caputo, M. (2024). The role of digital technologies in production systems for achieving sustainable development goals. *Sustainable Production and Consumption, 47*, 87–104. https://doi.org/10.1016/j.spc.2024.03.035.

Wang, N., Ma, M., & Liu, Y. (2020). The whole lifecycle management efficiency of the public sector in PPP infrastructure projects. *Sustainability, 12*(7), 3049. https://doi.org/10.3390/su12073049.

Willar, D., Trigunarsyah, B., Dewi, A. A. D. P., & Makalew, F. (2023). Evaluating quality management of road construction projects: A Delphi study. *The TQM Journal, 35*(7), 2003–2027. https://doi.org/10.1108/TQM-04-2022-0132.

Yaghootkar, K., & Gil, N. (2012). The effects of schedule-driven project management in multi-project environments. *International Journal of Project Management, 30*(1), 127–140. https://doi.org/10.1016/j.ijproman.2011.02.005.

Yaseen, Z. M., Ali, Z. H., Salih, S. Q., & Al-Ansari, N. (2020). Prediction of risk delay in construction projects using a hybrid artificial intelligence model. *Sustainability, 12*(4), 1514. https://doi.org/10.3390/su12041514.

Yin, R. K. (2020). *Case study research and applications: Design and methods* (6th ed.). Los Angeles.

Zou, P. X. W., Zhang, G., & Wang, J. (2007). Understanding the key risks in construction projects in China. *International Journal of Project Management, 25*(6), 601–614. https://doi.org/10.1016/j.ijproman.2007.03.001.